CURRENT STATUS AND FUTURE DIRECTIONS OF MAGNETIC FUSION ENERGY RESEARCH

by
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OUTLINE

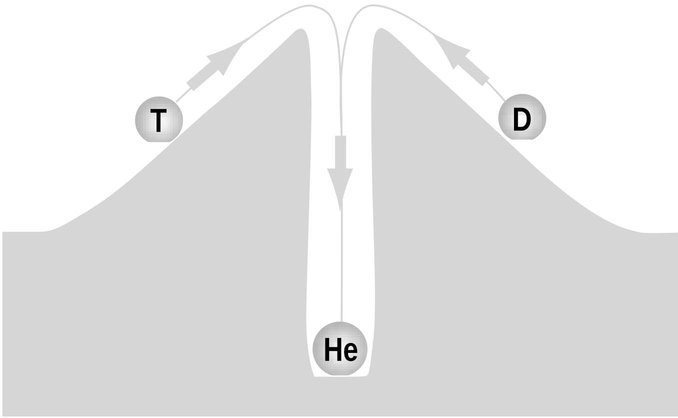
- Fusion basics
- Fusion research progress in the last two decades
- Further advancement couples scientific understanding with active control
- Worldwide collaboration will be needed to achieve fusion energy

FUSION BASICS

- **What is fusion?**
  - — Joining of small nuclei/atoms release usable energy
  - — Fusion keeps stars hot
  - — The easiest fusion reaction is

Deuterium (D) + tritium (T) → helium (H_e) + n + energy

- **How do you make them stick?**



- **Why fusion?**
  - — Plentiful fuel
  - — Minimal radioactive waste
  - — Minimal carbon waste
  - — Safe

- **What is a plasma**
  - — Plasma is a hot gas where e- are no longer attached to nuclei
  - — Hot plasma has fast moving nuclei
  - — At ~100 million degrees, the nuclei collides hard enough to fuse — like the sun

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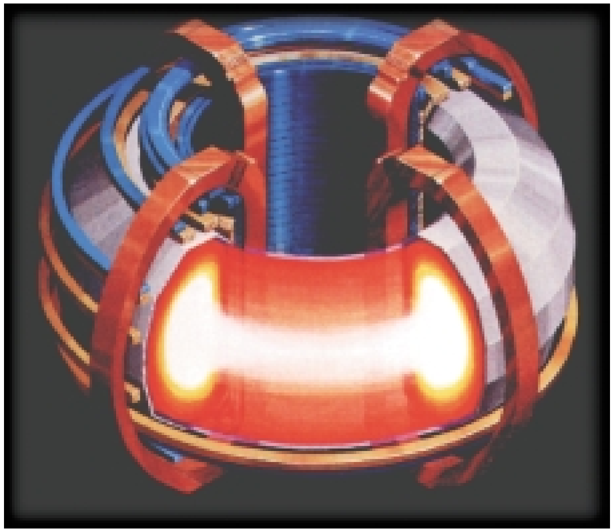
GENERAL ATOMICS

MAGNETIC CONFINEMENT

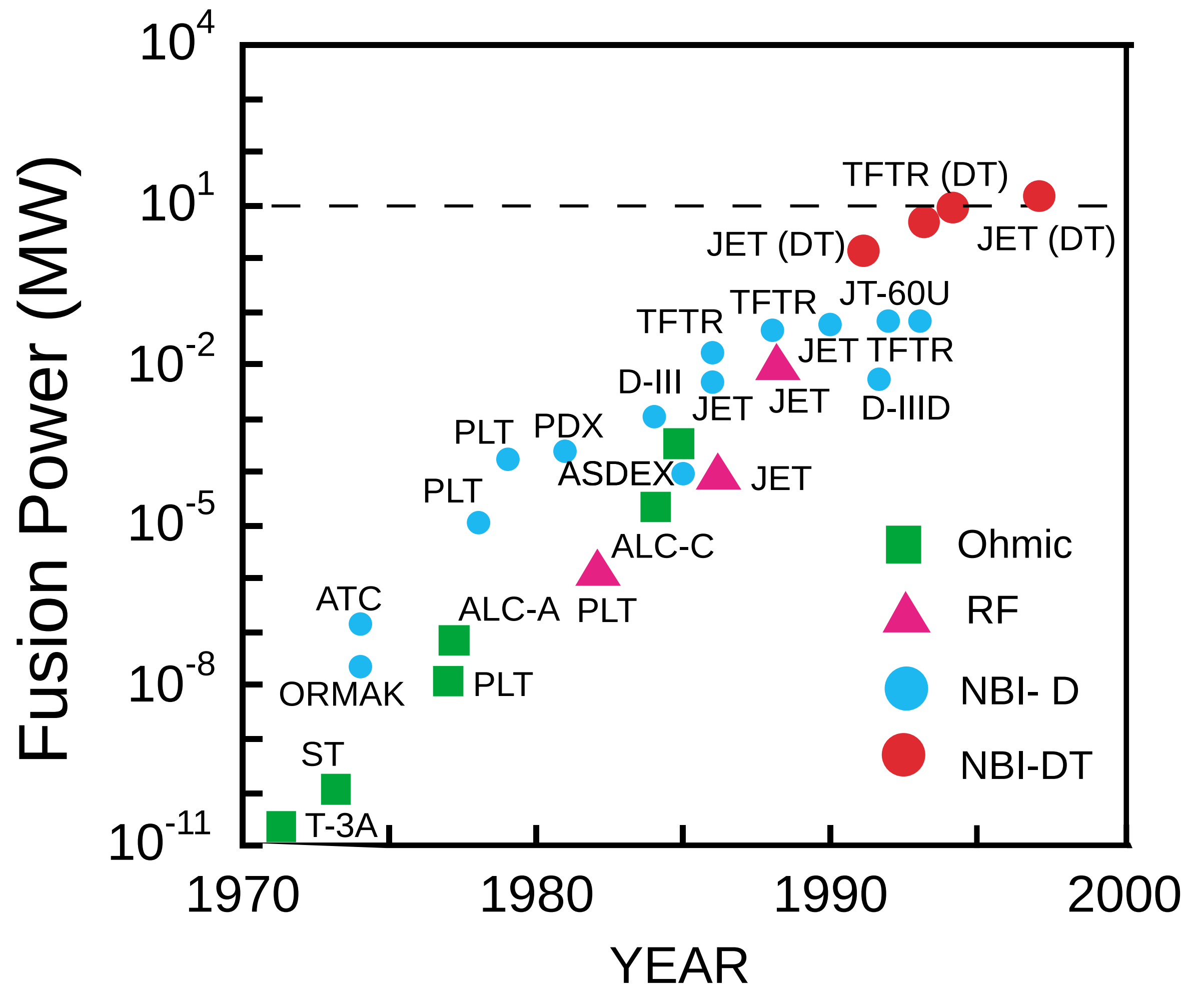
- One way to hold the hot plasma is with magnetic fields. The fields keep the plasma from touching the walls



- A major challenge is to make a "magnetic bottle" which holds the plasma quiescently
- Leading concept: the "tokamak" — An axisymmetric toroidal configuration with a strong toroidal plasma current and an external-coil supplied toroidal magnetic field strong enough to make the edge safety factor $q_{edge} = a\, B_T/R\, B_p > 2$

GENERAL ATOMICS

MAGNETIC FUSION DEVICES HAVE MADE EXCELLENT PROGRESS IN FUSION POWER



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GENERAL ATOMICS

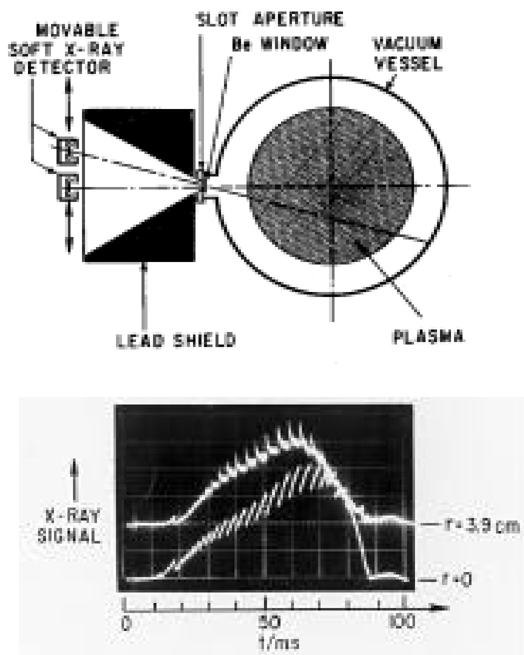
RESEARCH IN THE 70's AND 80's UNCOVERED INSTABILITIES WHICH PREVENTED THE PLASMA FROM GETTING DENSER, HOTTER, AND STABLE FOR LONG DURATION

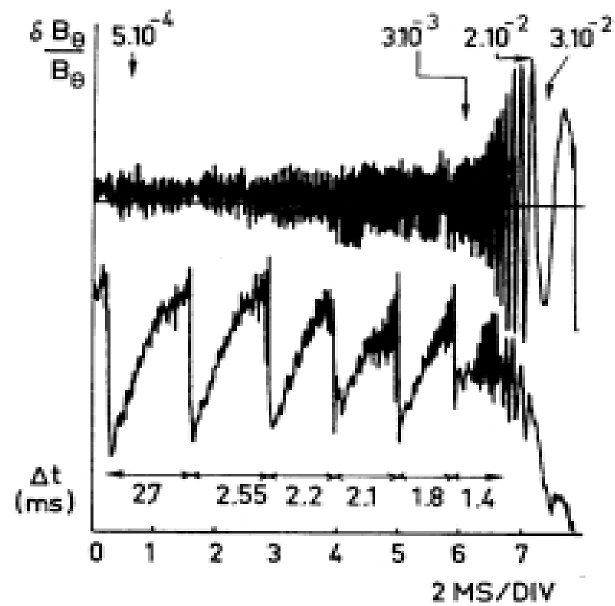
- The effects of plasma instabilities range from loss of the configuration to local transport

Spatial Scale of the Mode	Mode Description	Principal Consequence
~a	Global kink modes Ideal MHD (low n)	Disruptions β and I_p limits
$\sim\frac{1}{5}a$	Tearing modes Resistive MHD Ideal Ballooning ($n \rightarrow \infty$) Interchange	Macroscopic Transport Profile Modification
$\sim\frac{1}{10}a$	Edge Localized Modes	Periodic bursts at the edge
ρ_i	Ion Temperature Gradient Modes Drift Waves	Ion Transport
ρ_e	Electron Temperature Gradient Modes Drift Waves	Electron Transport

THEORY AND INNOVATIVE DIAGNOSTICS CONTRIBUTED TO THE UNDERSTANDING OF PLASMA INSTABILITIES

- Experimental diagnostics and theoretical work identified
  - — Resistive tearing modes
  - — Sawteeth
  - — Disruption mechanism





- Experimental arrangement of x-ray detectors and sawteeth on the ST tokamak

- Development of sawteeth and an m = 2 mode before a disruption of TFR

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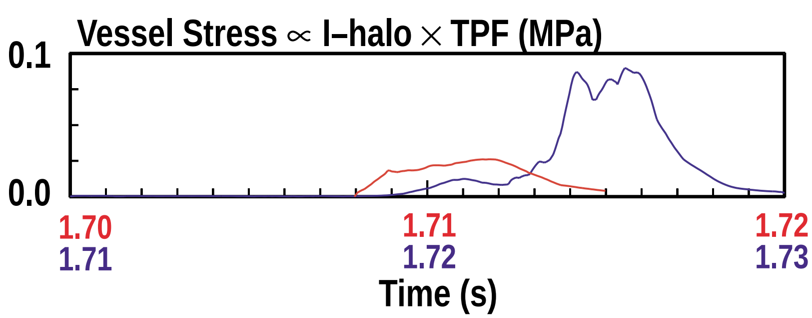
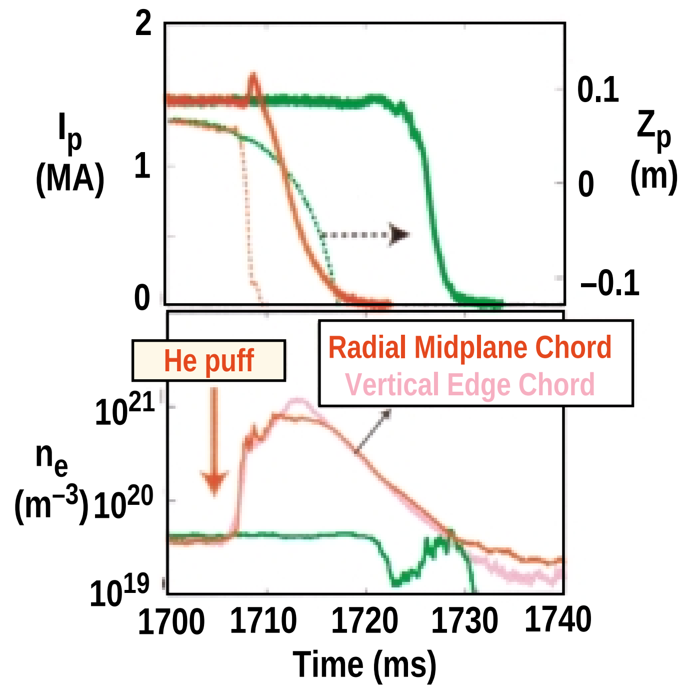
GENERAL ATOMICS

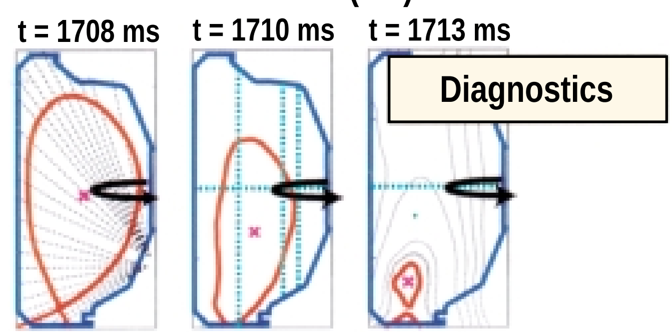
DISRUPTIONS CAN BE SUCCESSFULLY MITIGATED BY MASSIVE HELIUM GAS PUFF (DIII–D)

	No puff	He puff
Gas injection	- - - - -	10^{23} in ~10 ms
Peak I_{halo} (MA)	0.30	0.13
TPF	~2	1.2
Vessel movement (mm)	1.5 mm	<0.9 mm
W_{floor} (MJ)	0.73	<0.05
W_{rad} (MJ)	1.38	1.95

- No runaway electrons
- Reduced I_{halo} (Peak I_{halo}, TPF, Vessel movement)
- Radiation mitigation of divertor heat flux (W_{floor}, W_{rad})
- Forces on vessel reduced







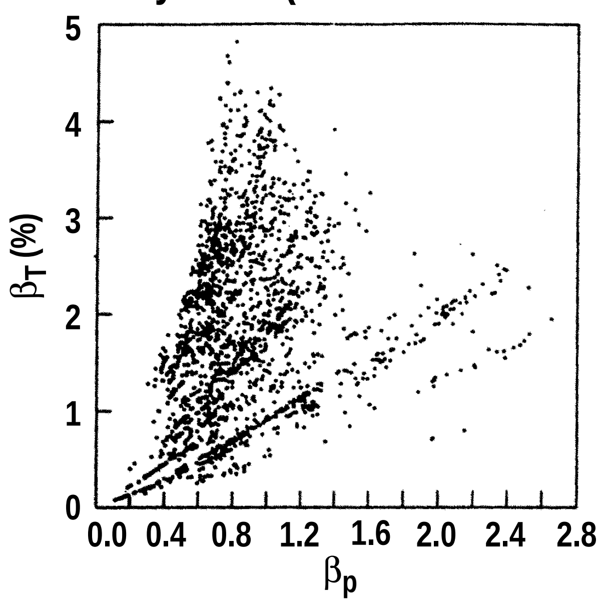
GENERAL ATOMICS

THE LIMITS OF PLASMA PRESSURE WHICH CAN BE STABLY CONFINED BY THE MAGNETIC FIELDS WERE ASCERTAINED

- Beta limits scalings were derived that fit well experimental results

  β = plasma pressure/magnetic pressure

Early work (Doublet III – 1984)



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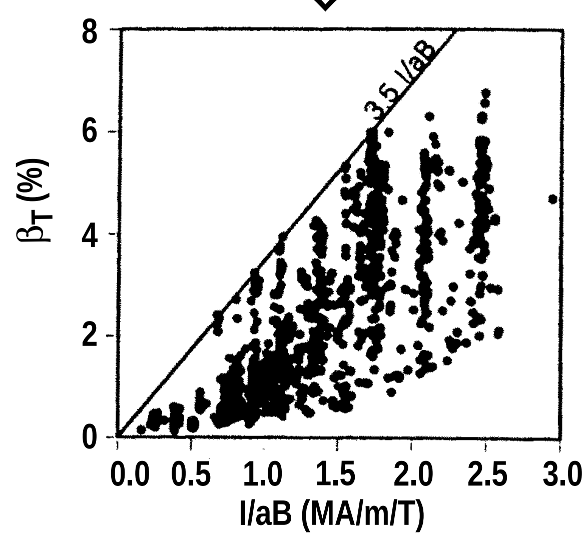
Theory calculations (1982–1984)

Troyon scaling

$$\beta_T\,(\%) = 2.8\,\frac{I\,(MA)}{a(m)\,B_T\,(T)}$$

Define $\beta_N = \beta_T/(I/aB)$

⇓



DIII–D Data (1988)

⇐

Fundamental equilibrium relation

$$\beta_T\,\beta_p = 25\left(\frac{1+\kappa^2}{2}\right)\left(\frac{\beta_N}{100}\right)^2$$

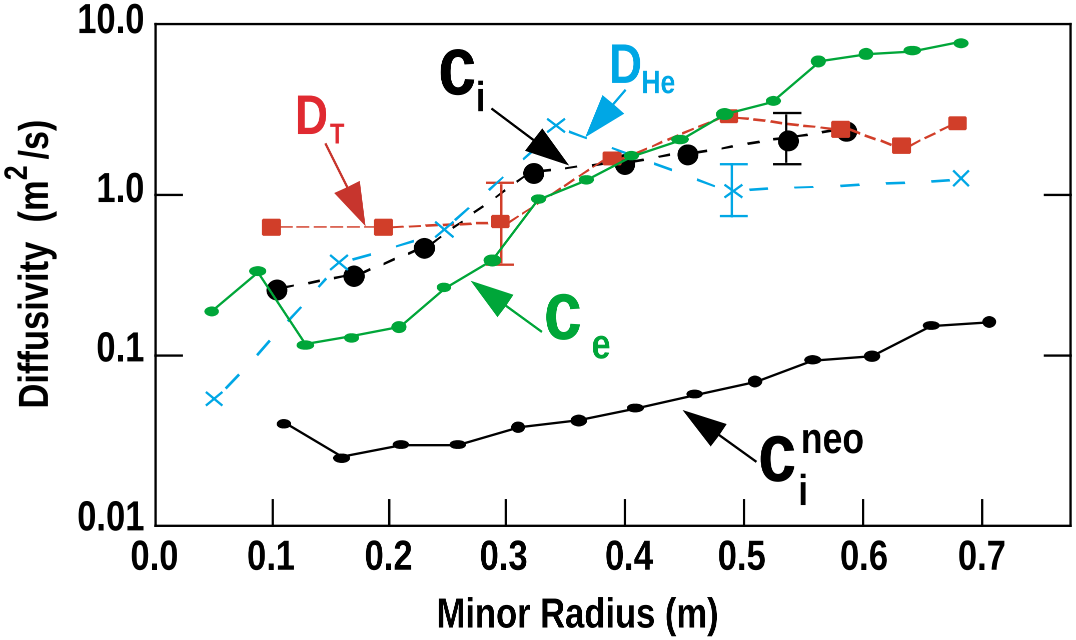
Bootstrap fraction

$f_{bs} = C_{bs}\,\varepsilon^{1/2}\,\beta_p$

Fusion power

$P_F \propto \beta_T^2\,B_T^4$

RADIAL TRANSPORT MEASUREMENTS INDICATE ELECTROSTATIC TURBULENCE IS IMPORTANT



- Experimental transport coefficients:: $D_T \approx D_{He} \approx \chi_e \approx \chi_i >> \chi_i^{neo}$
  - Excludes strong magnetic stochasticity
- Turbulence spectrum characterized by long wavelength modes ($k\rho_i \approx 0.2$)
  - Anisotropic spectrum
- Ion dynamics are important in turbulent spectrum
  - $T_i/T_i > n_i/n_i$

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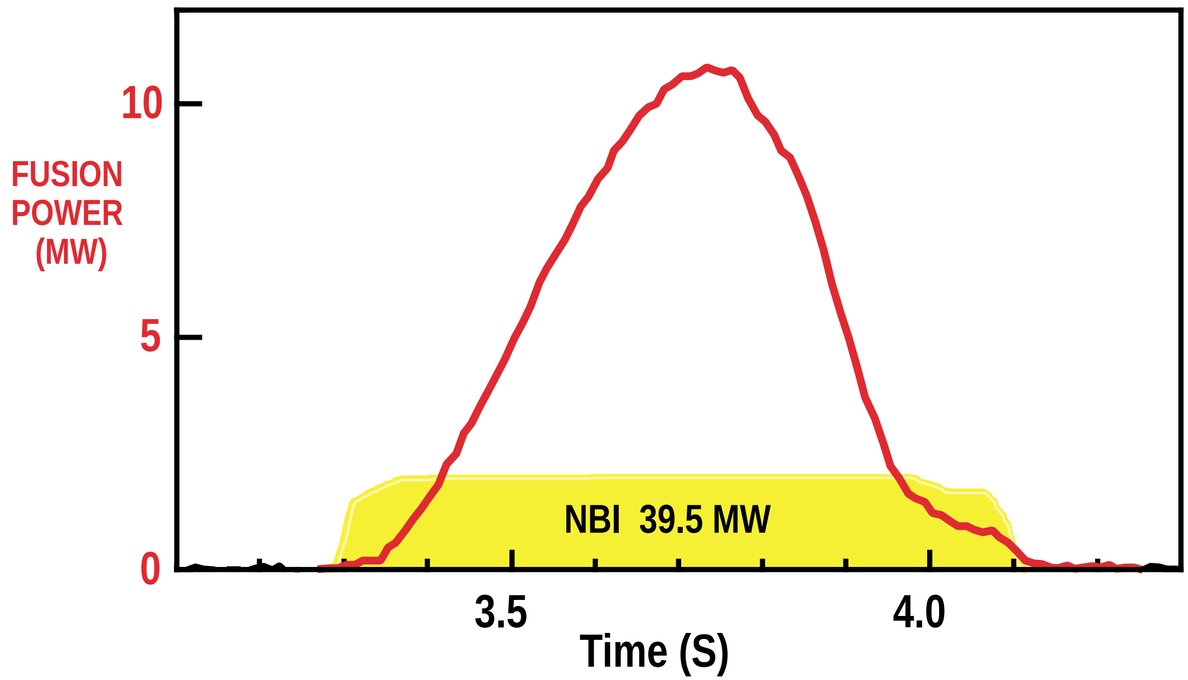
GENERAL ATOMICS

PLASMA STUDY IN D-T FUEL MIXTURE PRODUCED THE HIGHEST FUSION PERFORMANCE IN THE TOKAMAK FUSION TEST REACTOR (TFTR)

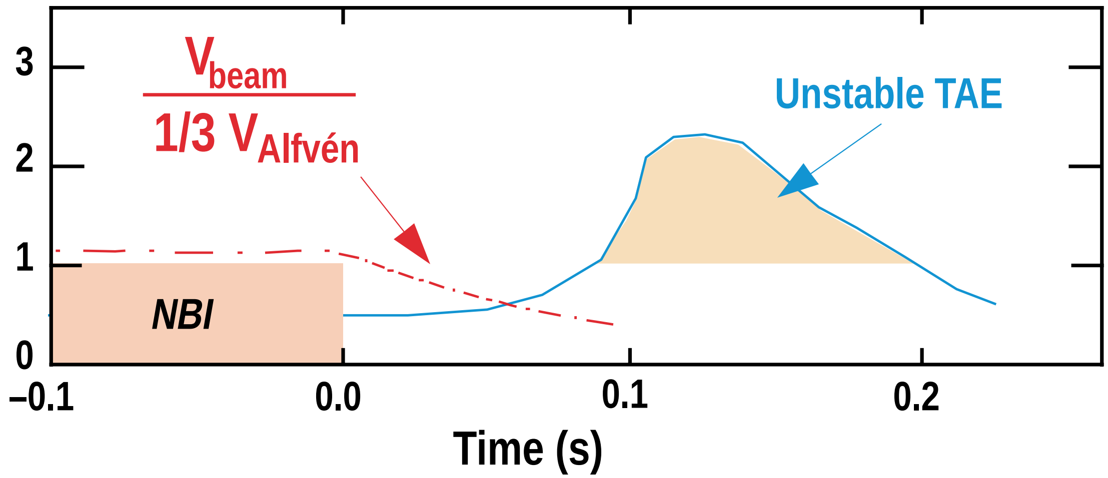


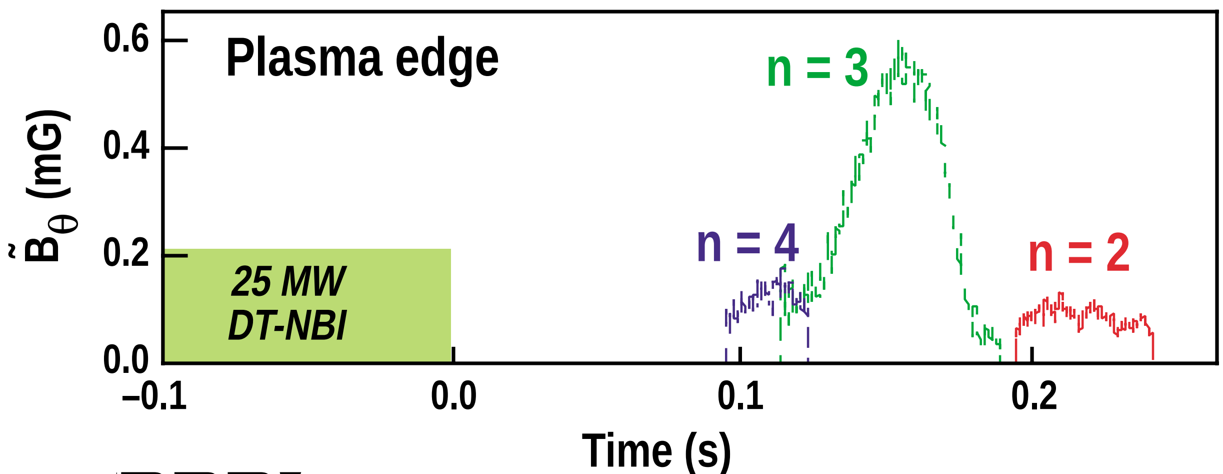
- Alpha particles are generally well-confined
- Under some conditions, a new kind of Alfvén instability can be excited

ALPHA DRIVEN TAEs IN WEAK SHEAR DISCHARGES

Theoretical Prediction:

- Reduce magnetic shear, beam damping and raise q(0)





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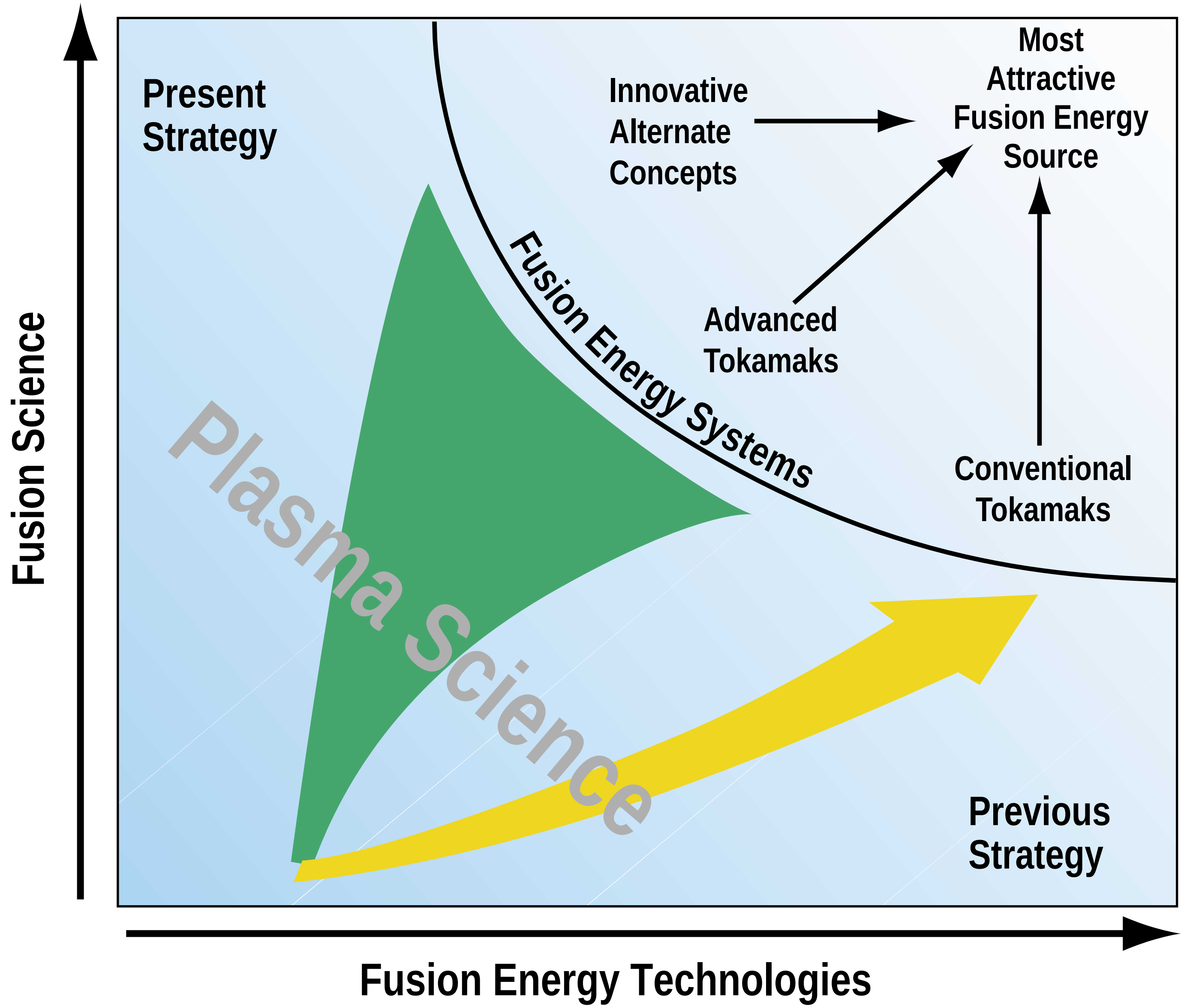
GENERAL ATOMICS

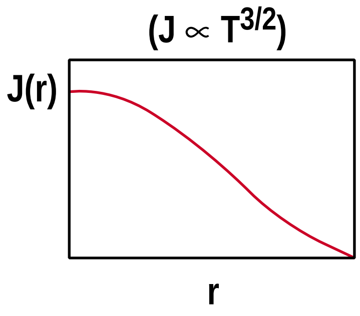
RESTRUCTURING OF THE U.S. FUSION ENERGY SCIENCES PROGRAM



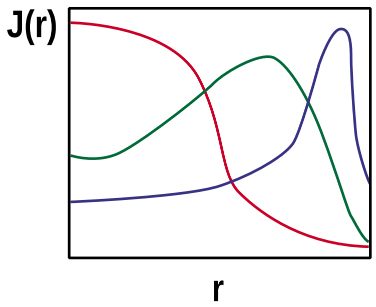
GENERAL ATOMICS

WHAT IS AN "ADVANCED TOKAMAK"

- A standard tokamak
  - Has a peaked current profile (q_0 = 1, sawteeth present) characteristic of ohmic heating
  - Therefore has a beta limit $\beta_N \leq 3$
  - Has standard confinement
  - Low bootstrap fraction

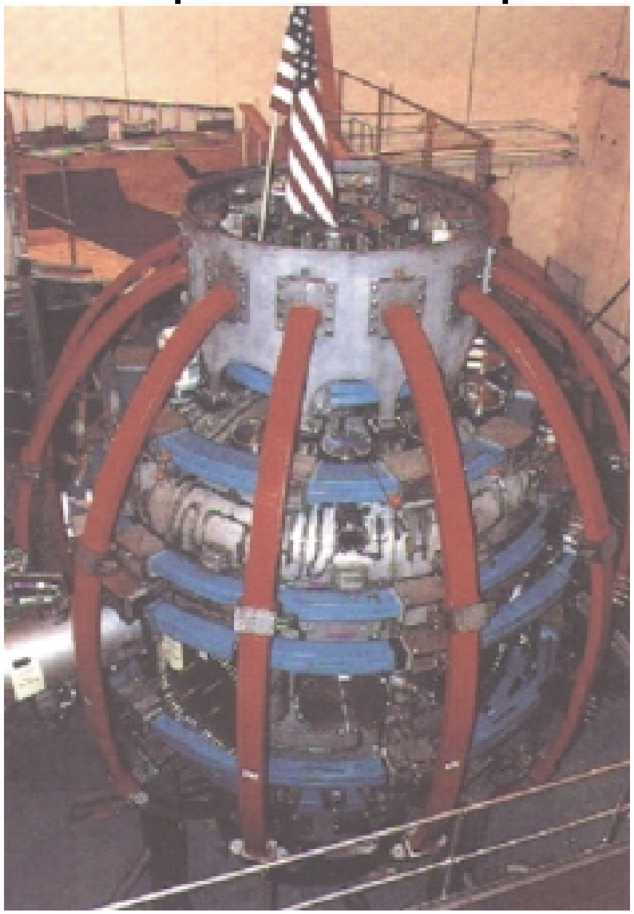


- An advanced tokamak
  - Frees the current profile from the ohmic constraint
  - With wall stabilization has potentially β_N up to 6
  - Exploits transport barriers for improved confinement
  - Has bootstrap fractions potentially $\rightarrow$ 100%
  - Potential for steady-state, reduced size fusion systems



US DOE ADVANCED TOKAMAK PORTFOLIO

National Spherical Torus Experiment

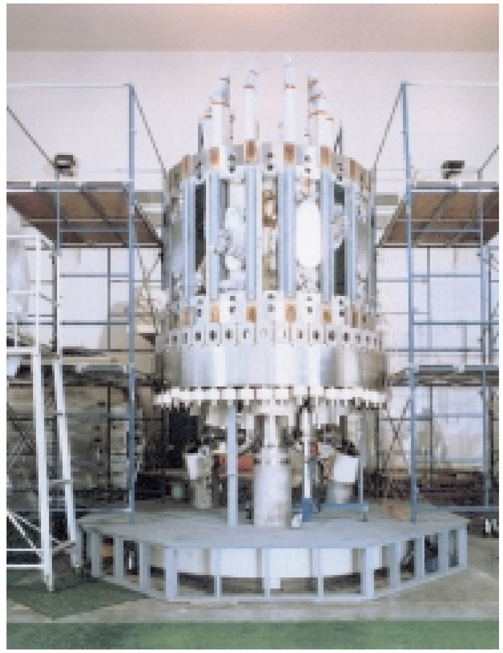


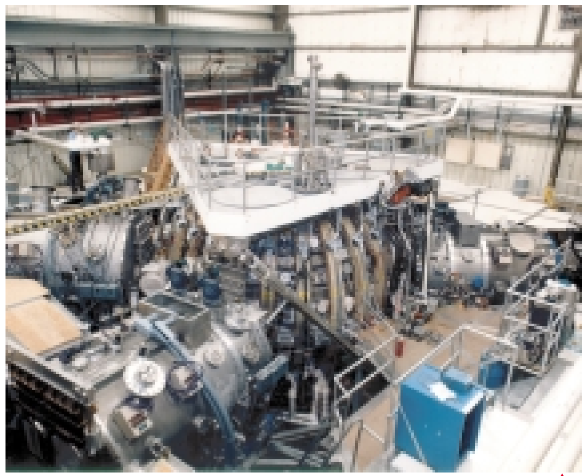
Princeton Plasma Physics Laboratory

Torus started operations in 1999

Massachusetts Institute of Technology

C–MOD started operations in October 1991





General Atomics

Doublet III (DIII–D) started operations in 1978

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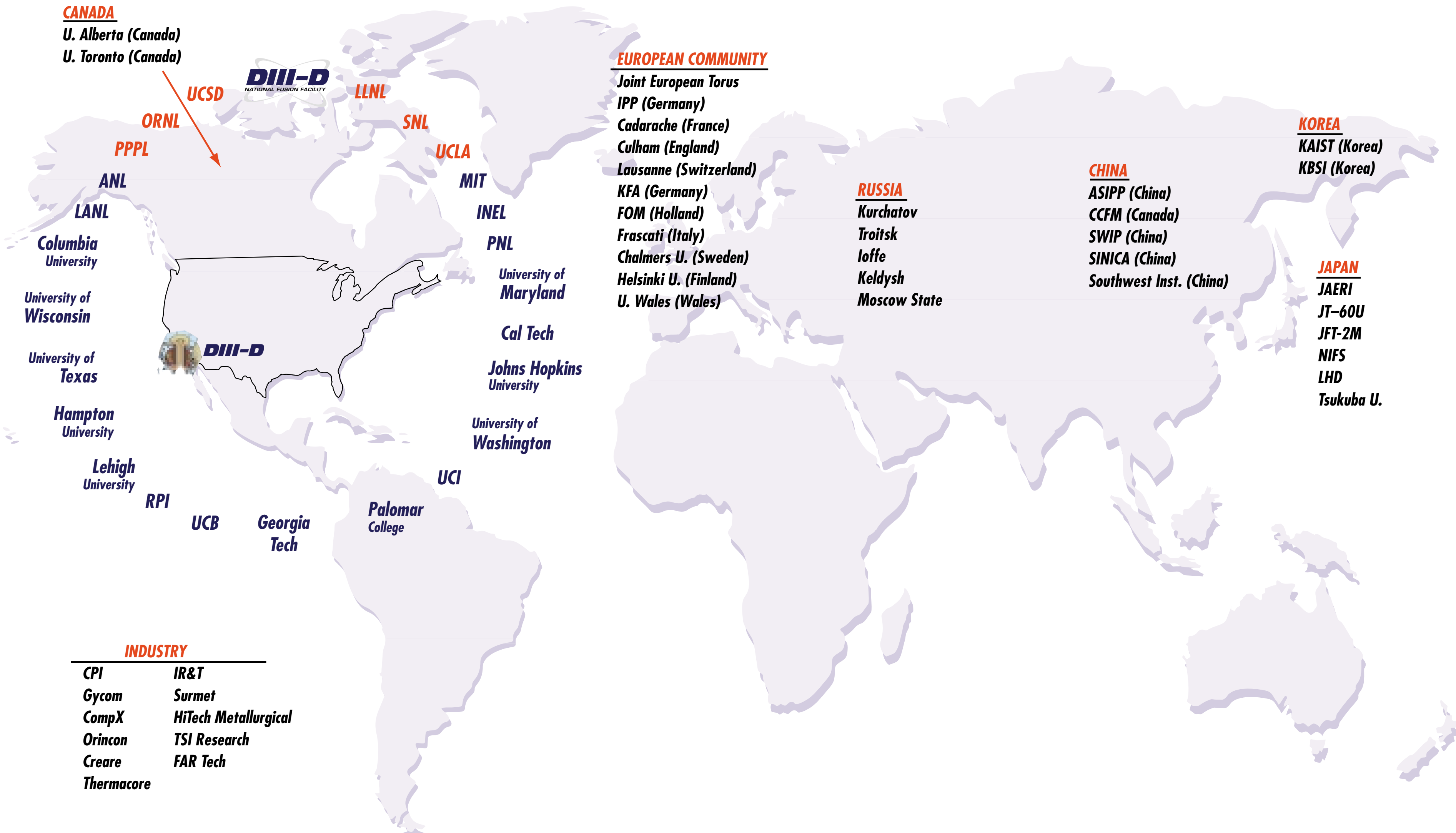
GENERAL ATOMICS

EFFECTIVE COLLABORATIONS ARE KEY TO THE DIII–D PROGRAM



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GENERAL ATOMICS

THE ADVANCED TOKAMAK ACHIEVES OPTIMIZATION OF ITS PERFORMANCE THROUGH UNDERSTANDING OF FUNDAMENTAL SCIENTIFIC ISSUES

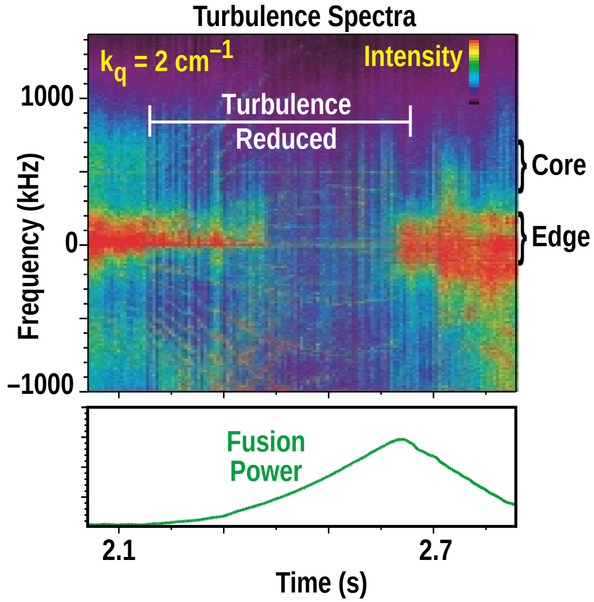
- **Transport and turbulence**
  - What are the fundamental causes of heat loss in magnetically confined plasmas, and how can heat losses be controlled?

- **Plasma fluid behavior and macrostability**
  - What are the fundamental causes and nonlinear consequences of plasma pressure limits in magnetically confined plasma systems?

- **Wave-particle interaction**
  - What are the fundamental causes and nonlinear consequences of wave interactions with thermal and non-thermal particles?

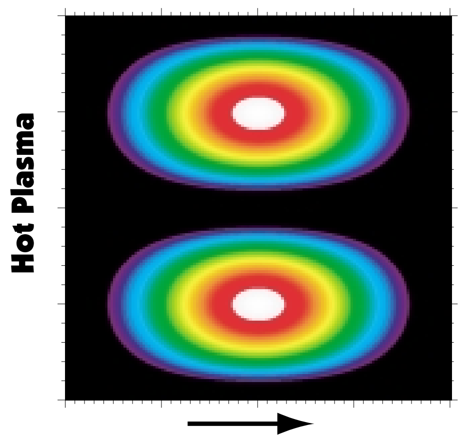
- **Plasma-wall interaction**
  - What are the fundamental processes occurring near the boundary of a confined plasma and how can the interaction between the plasma and material surfaces be controlled?

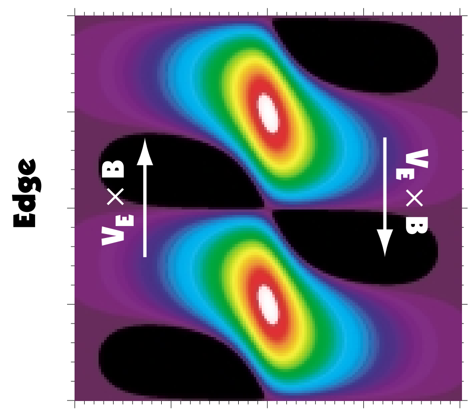
GOOD PLASMA CONFINEMENT (LOW HEAT LOSS) IS IMPORTANT FOR HIGH PERFORMANCE AND COST EFFECTIVENESS



Turbulence limits confinement and performance in present day tokamaks

Velocity shear $V_{E\times B}$ effectively stabilizes turbulence





Shear produces regions of reduced transport (transport barriers) and improved confinemnt

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GENERAL ATOMICS

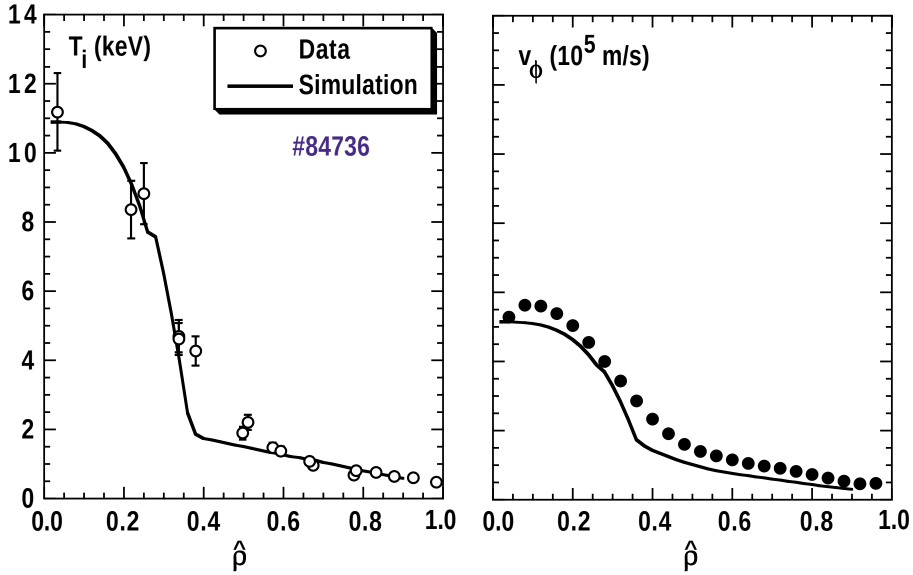
GOOD PLASMA CONFINEMENT (LOW HEAT LOSS) IS IMPORTANT FOR HIGH PERFORMANCE AND COST EFFECTIVENESS

A number of means are being used at DIII–D to directly or indirectly influence velocity shear to improve confinement

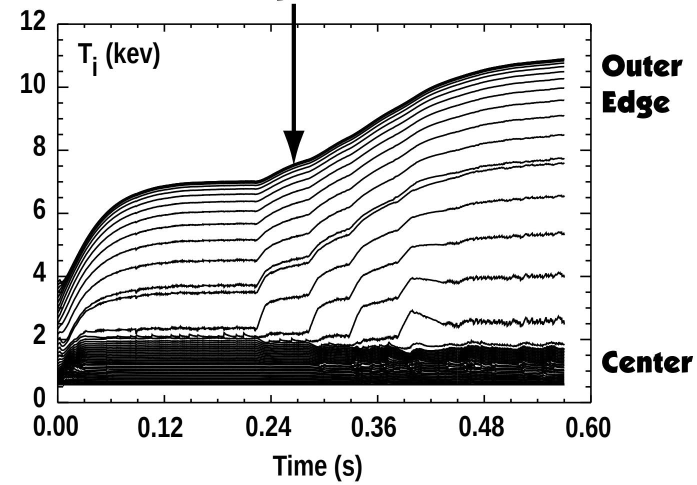
- **Neutral beam injection (through induced rotation)**
- **Impurity injection**
- **Electron cyclotron waves are particularly valuable because they can be localized**

Prediction of recent ion transport barrier models of shear stabilization argree with experimental results

Predicted and observed profiles show existance of transport barrier



Stepwise formation of transport barrier



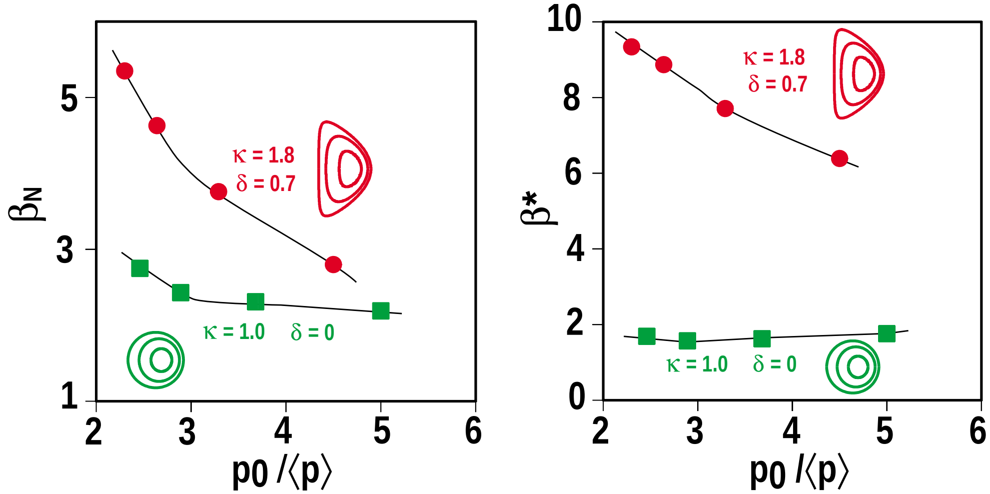
GENERAL ATOMICS

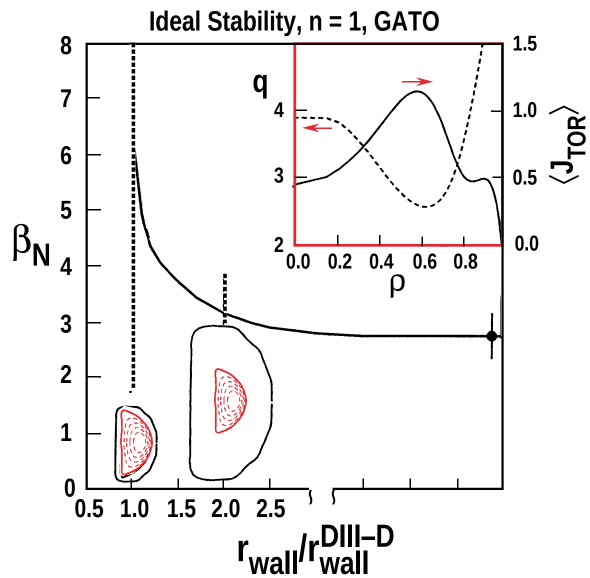
MAXIMIZING PLASMA STABILITY FOR OPTIMAL PERFORMANCE

- Close contact with theory allows detailed understanding and continued progress

Control of plasma cross section and current profile are important tools

Elongated dee shapes and control of current profile improve stability against ideal modes





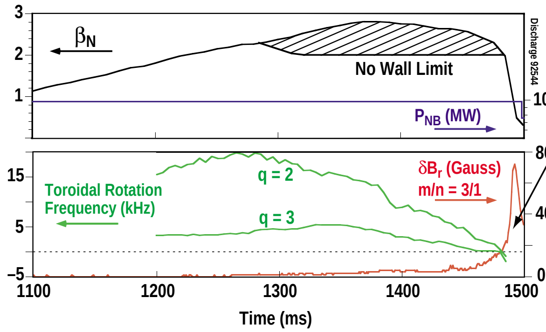
Additional ECH power gives us an important tool to optimize stability

The presence of a conducting wall further increases limiting beta

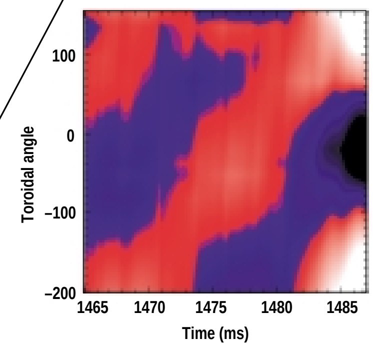
MAXIMIZING PLASMA STABILITY FOR OPTIMAL PERFORMANCE

Slower growing resistive wall modes destabilizing plasma in presence of resistive walls

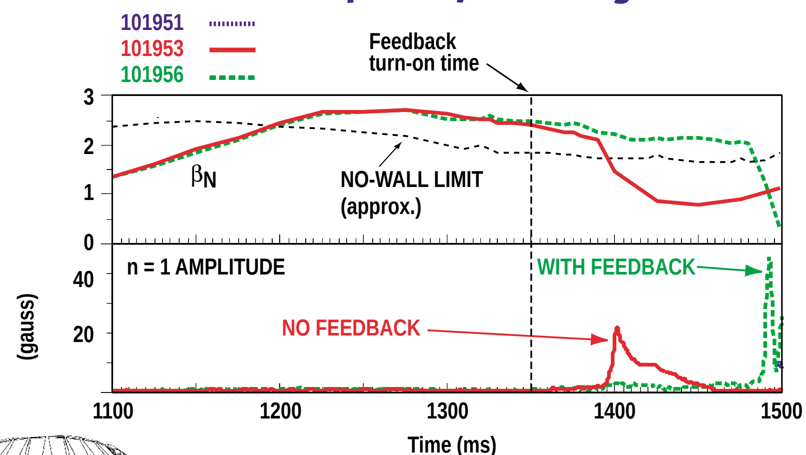
Plasma rotation can stabilize these modes and allows higher performance (β) neutral beams provide the needed angular momemtum

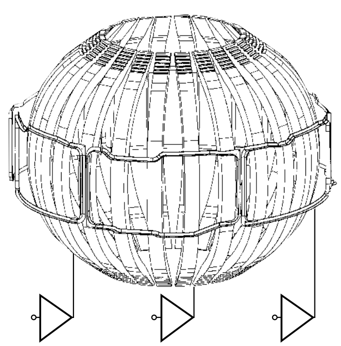


3/1 Mode Terminate Plasma

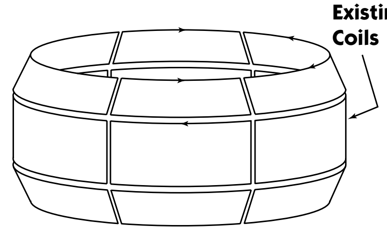


Active stabilization is achieved using non-axisymmetric external coils to simulate a perfectly conducting wall





Expanded Coil Set (2002) Will Improve This Tool



CURRENT PROFILE CONTROL FOR STEADY-STATE OPERATION

- Eliminates need for ohmic heating transformer
- Manage the current distribution to optimize stability and confinement

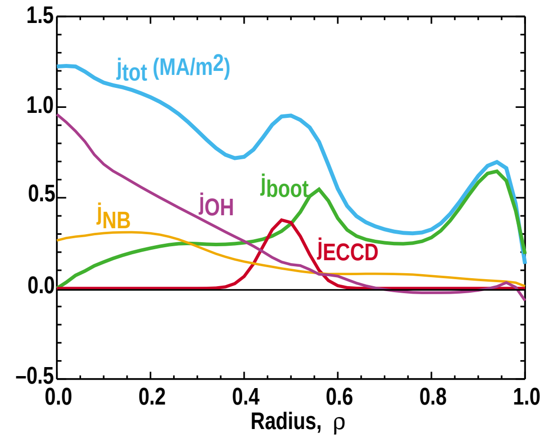
Plasma current has several components

— **Ohmic from transformer**

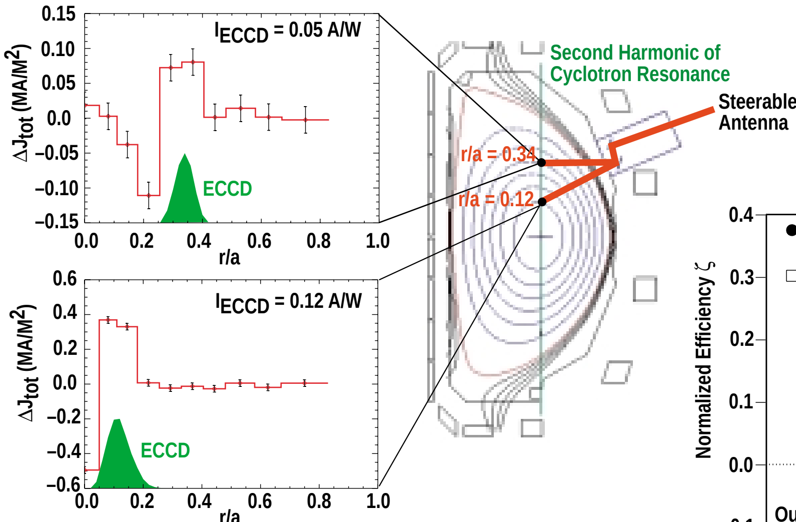
— **Bootstrap current — a self generated current**

— **Neutral beam driven**

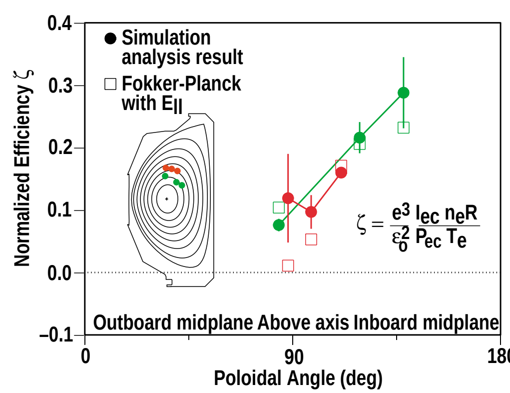
— **Electron cyclotron wave driven**



Electron cylclotron waves provide localized current drive needed for profile control with noteworthy flexibility



New launcher from PPPL allows control of beam direction



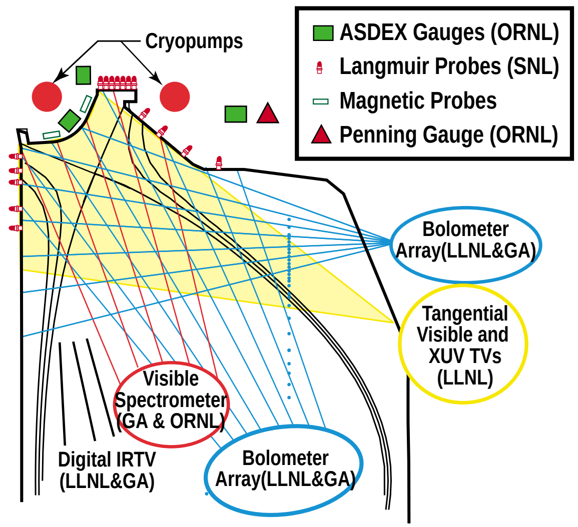
Theory and experiment closely coupled

DIVERTORS MANAGE PARTICLE AND HEAT FLOW AT EDGE OF PLASMA

- Remove fusion products (ash) and impurities
- Manage multi megawatt plasma heat loads

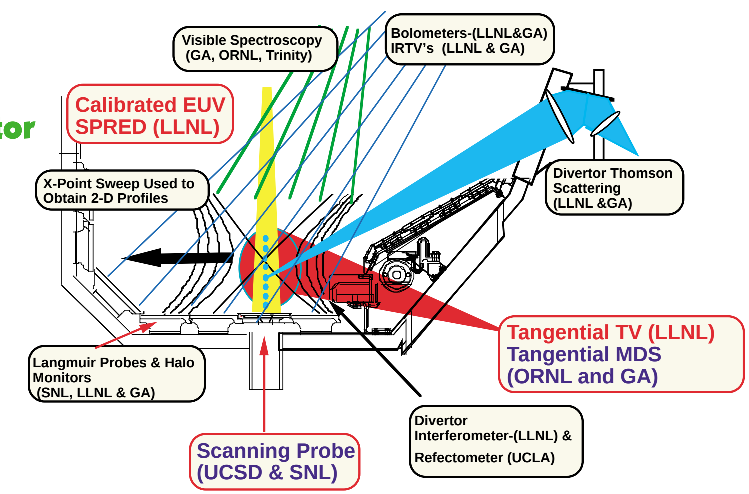
Two different divertor configurations in DIII–D allow studies of different plasma shapes and coupling to the divertor

Closely coupled upper divertor optimized for high performance advanced tokamak discharge

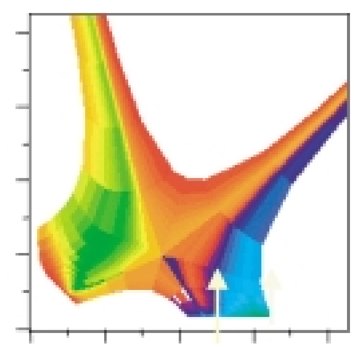


Extensive Diagnostics allow understanding of the underlying divertor science

Open lower divertor allows detailed diagnostics and modeling



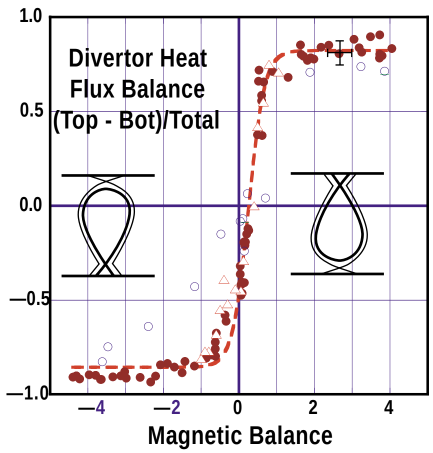
Computer models and understanding of complex divertor processes

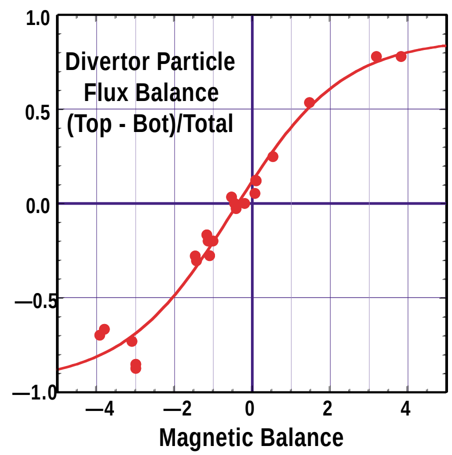


GENERAL ATOMICS

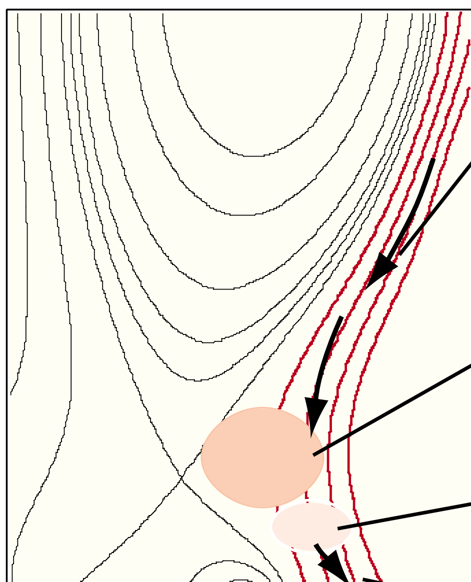
DIVERTORS MANAGE PARTICLE AND HEAT FLOW AT EDGE OF PLASMA

External magnetic coils control heat and particle flow to the divertor





Divertors offer a solution to power and particle management at edge of plasma



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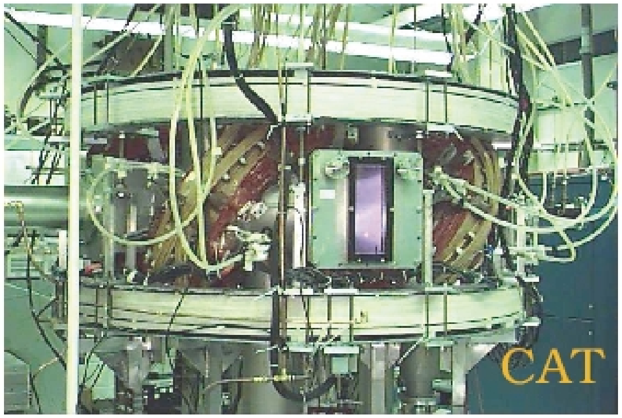
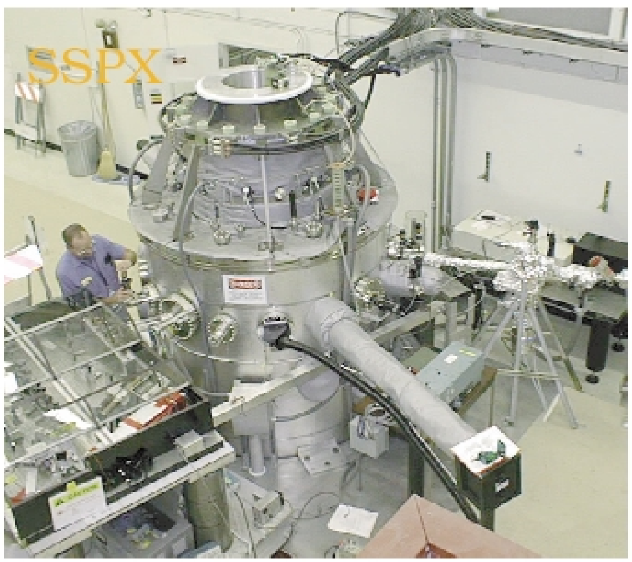
GENERAL ATOMICS

US DOE INNOVATIVE CONFINEMENT CONCEPTS PORTFOLIO

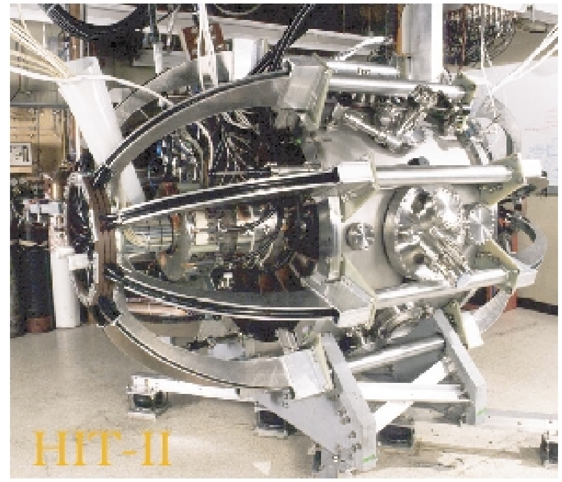


Concept Auburn Torsatron
Auburn University, Auburn Alabama

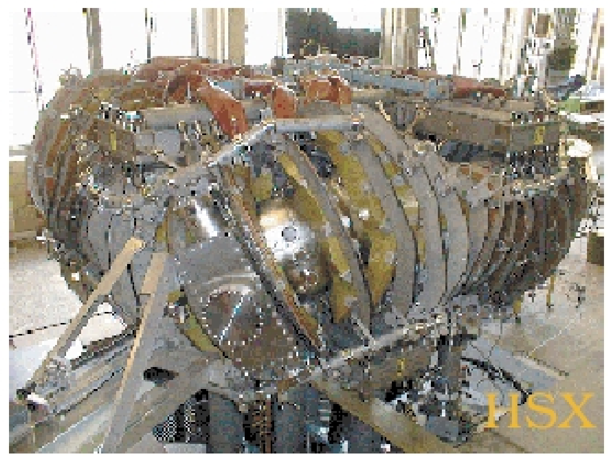


Sustained Spheromak Plasma Experiment
Lawrence Livermore National Laboratory

Levitated Dipole Experiment
Columbia University/Massachusetts Institute of Technology

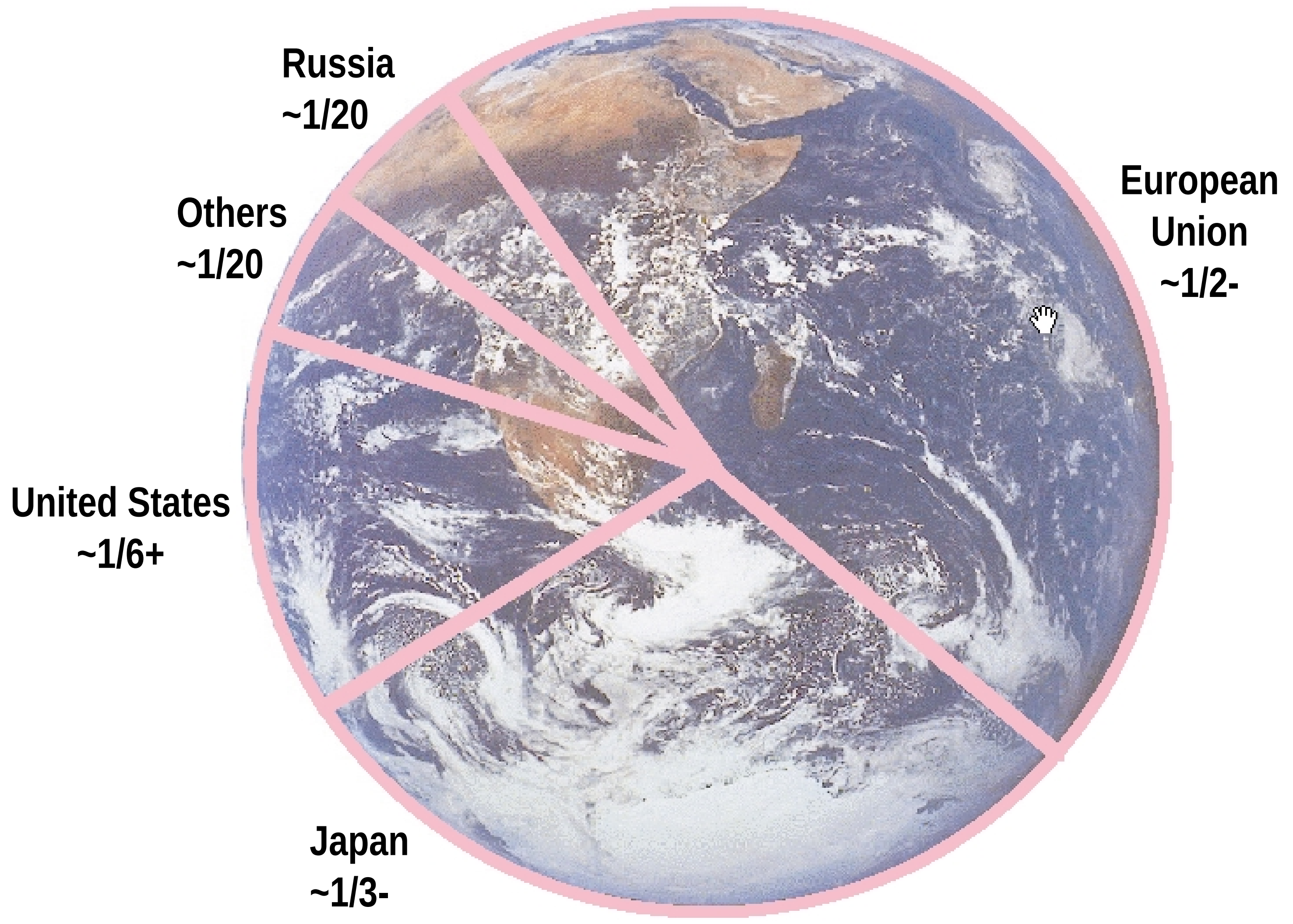


Helicity Injected Torus-II Experiment
University of Washington, Seattle



Helicity Symmetric Experiment
University of Wisconsin, Madison

WORLD MAGNETIC FUSION EFFORT (2000)



[Relative levels based on published budgets, estimates of personnel not included in budgets and rough conversions to dollars]

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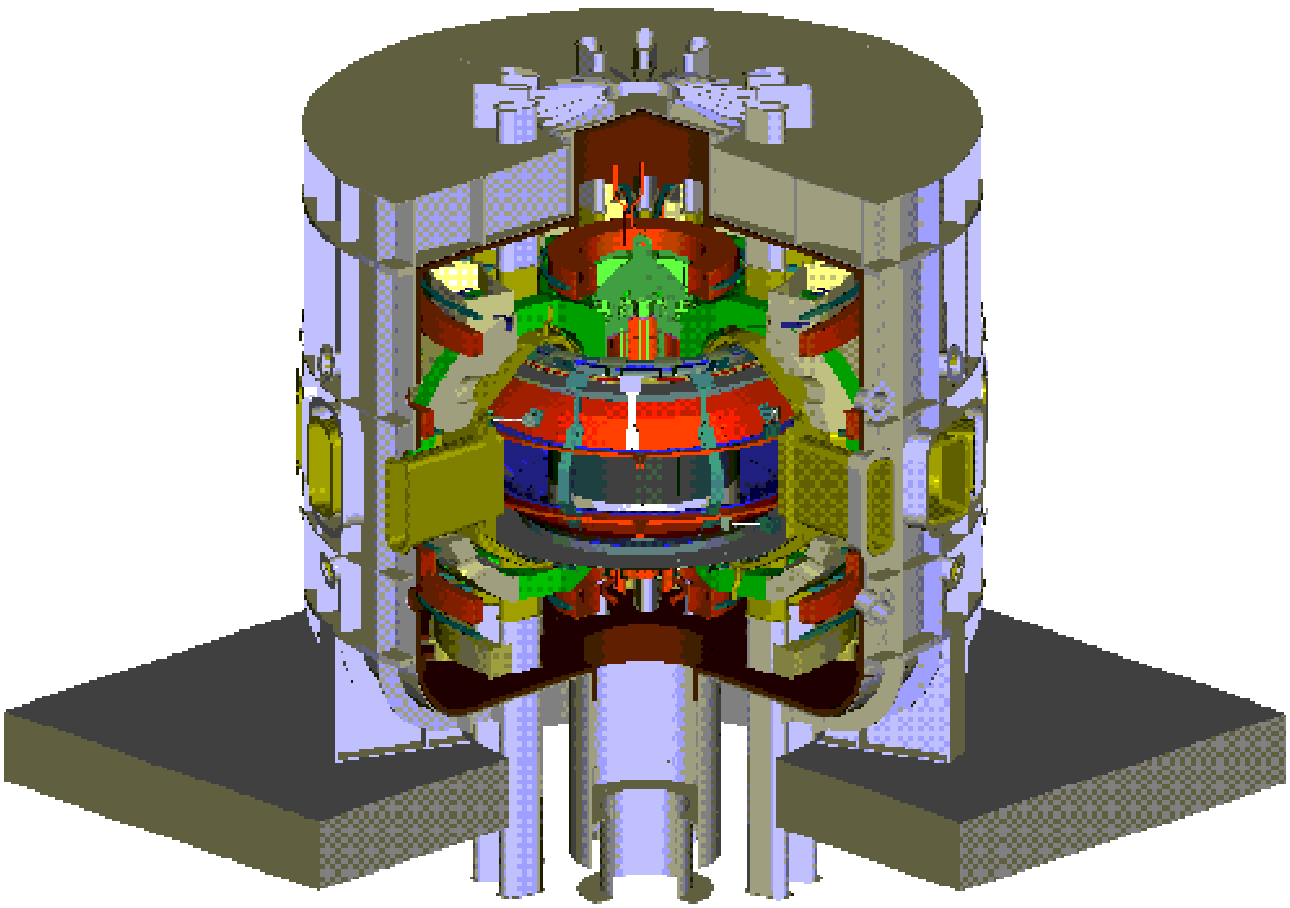
GENERAL ATOMICS

EXTENDING THE ADVANCED TOKAMAK: KSTAR (KOREA)

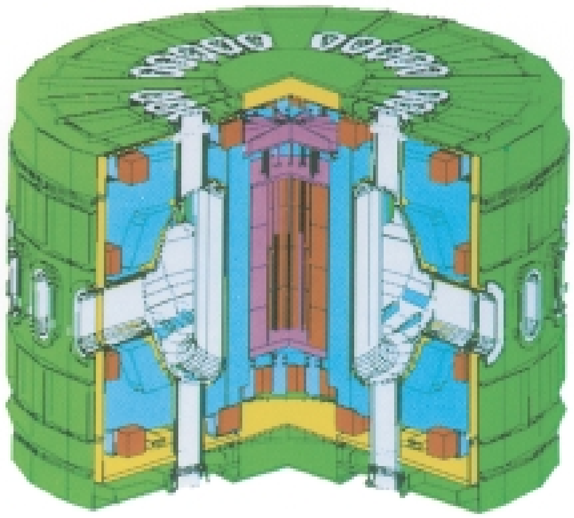


- 20–300 s pulse length (S/C technology)
- B = 3.5 T, I = 2 MA
- R = 1.8 m, a = 0.5 m
- Double-null divertor, $\kappa = 2$, $\delta = 0.8$
- 16-27 MW profile control: (neutral beam, ion cyclotron, lower hybrid)

First plasma 2003

HT–7U ADVANCED TOKAMAK – HEFEI, CHINA
INSTITUTE OF PLASMA PHYSICS ACADEMIA SINICA

HT–7U



ASIPP

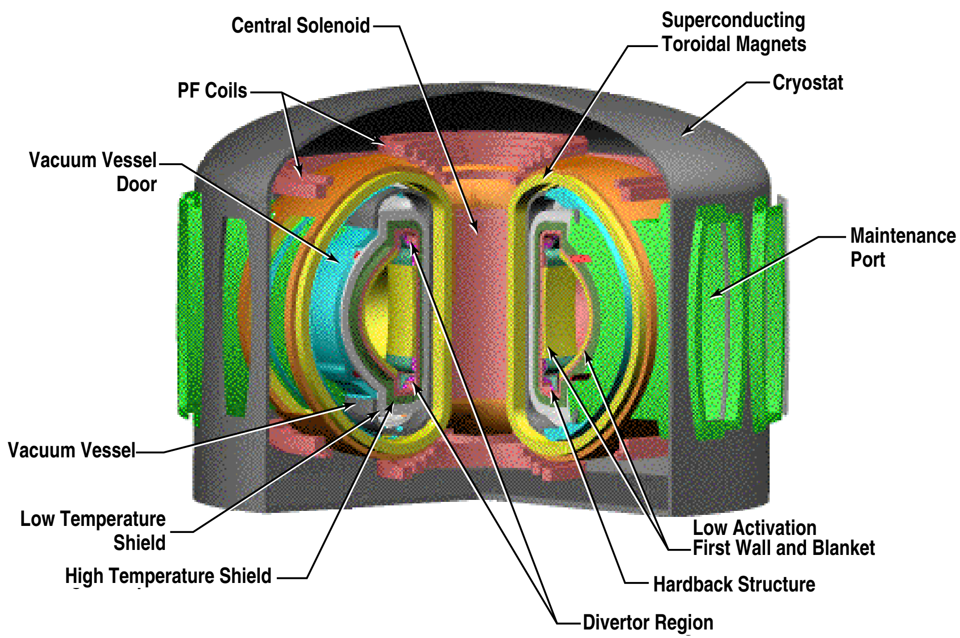
HT–7

Construction: Approved
Conpletion: mid 2003

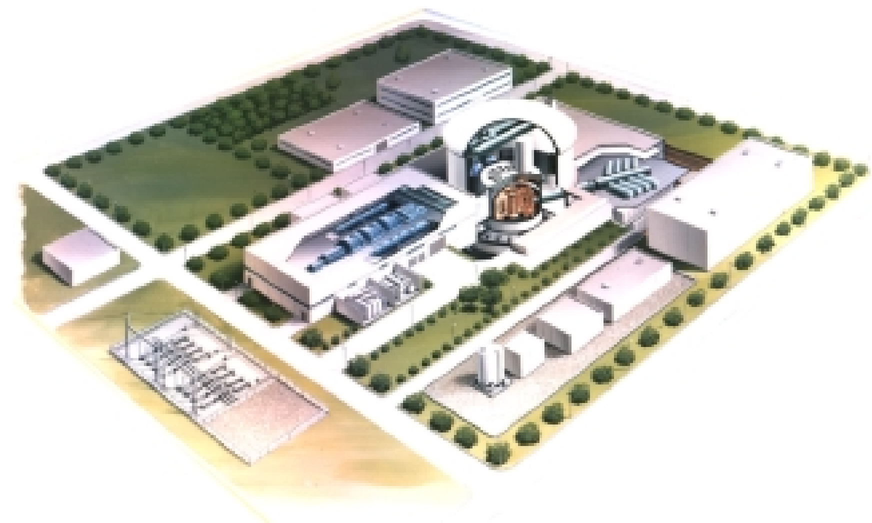
R/a = 1.7/0.4 m
B = 3.5 T
I = 1 MA
κ = 1.6 – 2.0
δ = 0.4 – 0.8

THE ADVANCED TOKAMAK LEADS TO AN ATTRACTIVE FUSION POWER PLANT

- The U.S. ARIES — RS system study



- The Japanese SSTR system study



- Attractive features
  - Competitive cost-of-electricity
  - Steady-state operation
  - Maintainability
  - Low-level waste
  - Public and worker safety

	Conventional	AT
Size, major radius (m)	8	5
COE $/kWhr	~13	~7
Power cycle	Pulsed	Steady state

SUMMARY

- Research in the tokamak has greatly advanced fusion energy science

- Tokamak research has shown fusion energy is feasible

- Advanced Tokamak research seeks to find the ultimate potential of the tokamak as a magnetic confinement configuration
  - Anticipated results point to practical and attractive fusion energy

- The tokamak is scientifically and technically ready to proceed to burning plasma and/or steady-state next steps

- Realization of fusion energy requires worldwide collaboration