The path to magnetic fusion energy and the Princeton Plasma Physics Lab.

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Outline

• Introduction and motivation
• ITER
• Issues and Challenges
• PPPL research strategy
Fusion Requires High Temperature Plasmas

• D + T → α (3.5 MeV) + n (14.1 meV)  
  highest cross section at lowest energy

• For thermal distributions, reaction rate  
  peaks ~ T = 800 MºC (~70 keV)

• Peak energy gain for T ~ 170 MºC  
  (~ 15 keV)

There, reaction rate  
  \( n_D n_T \langle \sigma v \rangle \propto n^2 T^2 \propto p^2 \)  
  ⇒ want to maximize pressure

• For self-heated plasma  
  fusion heating rate (\( \alpha \)) = energy losses  
  ⇒  \( n \tau_E > 2 \times 10^{20} \text{ (m}^{-3} \text{ sec}^{-1}) \) for T = 20 keV  
  \( \tau_E \) is the energy confinement time  
  (J.D. Lawson, 1957)
Deuterium-Tritium Fusion Reaction

Energy Multiplication
About 450:1

Plasma self-heating
Tritium replenishment

Deuterium (D)
Tritium (T)

Alpha Particle

Fast Neutron

He\(^4\)
Fusion Plasma

Fusion power density in sun $\sim 300$ Watt/cubic meter,

In fusion laboratory plasma $\sim 10$ MWatt/cubic meter
Why fusion?

• Nearly inexhaustible
  Deuterium from water, Tritium from lithium+neutron

• Available to all nations
  reduced conflict over resources

• Clean
  no greenhouse gases, no acid rain

• Safe
  no runaway reactions or meltdown;
  only short-lived radioactive waste
Magnetic Confinement

• For straight magnetic field lines, charged particle motion \( \perp \) to \( B \) is constrained

\[
m \frac{d\vec{v}}{dt} = q(\vec{E} + \vec{\nabla} \times \vec{B}) + \mathbf{C}
\]

\( \Rightarrow \) collisional diffusion \( D_{\perp} \sim \lambda^2 \nu_{\text{coll}} \rightarrow \rho^2 \nu_{\text{coll}} \)

magnetic moment \( \mu = \frac{mv_{\perp}^2}{2B} \)

• Only successful way to confine motion \( \parallel \) to \( B \) is to bend \( B \) into a torus

• \( |B| \propto 1/R \)

Additional force = \(-\mu \nabla B\) causes single particles to drift vertically

\[
\mathbf{v}_D = \mu B \nabla B / Z q B^2
\]

for 10 keV, \( 10^{20} \) m\(^{-3} \)

\( B = 1 \) T

\( \rho_i \sim 1 \) cm

\( \lambda \sim 10 \) km
**Helical Magnetic Confinement**

- Most successful strategy: use helical $B$ with field lines on nested magnetic surfaces.

- During parallel motion along $B$, $B \times \nabla B$ compensates at top and bottom of torus.

- Simplest strategy: make system toroidally symmetric: e.g. Tokamak
  - generate helical field using external coils + induced plasma current
  - Helicity of $B$ parameterized as "magnetic rotational transform"
    - $= \# \text{ transits short way} / \# \text{ long-way}$

  symmetry $\Rightarrow p_\phi$ conserved,
  $\Rightarrow$ particle orbits confined.
  $\Rightarrow$ $B$ field lines confined to nested toroidal surfaces

Issue: how to sustain current?
Tokamaks: Very successful, but Loss of Energy Faster than Prediction

- Tokamaks have achieved fusion parameters: $T \sim 500 \, \text{M}^\circ\text{C}$! $\tau_E > 1$ sec
  - Have produced up to 17 MW of fusion power (gain $\lesssim 1$)
- Additional processes: turbulence driven by huge thermal gradients
- Better than no magnetic field by $>10^6$
Simulations predict turbulent eddies disrupted by strongly sheared plasma flow.

Turbulent fluctuations are suppressed when shearing rate exceeds growth rate of most unstable mode.

- Ion Transport reduced to collisional level!
- Turbulence generated self-generated flows crucial for saturation.
Most Dangerous Eddies: Transport long distances

Sheared Eddies Less effective

Break up from secondary instabilities

Sheared Flows can Reduce or Suppress Turbulence

\[ \omega_{E \times B} \equiv \nabla \nu_{E \times B} \sim \gamma \]
Gyrokinetic Analysis of Turbulence Has Broad Scientific Importance

- Astrophysics turbulence dynamics: cascading of MHD turbulence to small ion scales is of fundamental importance (only electrons radiate...).
- Fusion’s gyrokinetic formalism can be applied to astrophysical turbulence, w/ applications to shocks, solar wind, accretion disks.
- Laboratory plasmas provide validation of formalism.
Experiments produced substantial fusion energy

- Enough for ~3000 houses
- JET (EU) produced 16MW for ~1 sec. in 1997
Recent progress in fusion power limited by lack of facilities, not science
Tokamak Pressure Limits Set by Instabilities

Tokamak pressure limit extensively studied

- Determined by instabilities
  - Ideal-like instabilities $\rightarrow$ disruptions
  - Saturated instabilities: degraded confinement

- Instabilities often involve plasma current

Can cause strong changes to confining magnetic fields $\rightarrow$ Disruptions

- Onset of instabilities in good agreement with theory

$$\delta W = \frac{1}{2} \int \delta r^3 \left\{ \frac{1}{\mu_0} \right\} \delta B^2 + \frac{B^2}{\mu_0} \nabla \cdot \xi + 2 \xi \cdot \kappa + \gamma p \nabla \cdot \xi^2 - J_\parallel (\xi \times b) \cdot \delta B - 2 (\xi \cdot \nabla p) (\kappa \cdot \xi)$$

current limit  pressure limit
Next Step: Burning Plasmas in ITER

Partnership of US, China, EU (45%), India, Japan, Russia, S.Korea;

Located in France. US contributions managed by ORNL, PPPL, SRNL.

ITER goals: 500 MW for >500s, power gain Q > 10

Understanding of:
- Sustaining hot burning plasma by fusion reactions.
- Confinement of reactor-scale plasma
- High gain dynamics
ITER site preparation in France

Plan for 2020 Operation
ITER will Study Wide Range of Physics
In the Burning Plasma Regime

• **Stability:** Extend the understanding of pressure limits to much larger scale plasmas.

• **Energetic particles:** Study strong heating by fusion $\alpha$-particles, in new regimes where multiple instabilities are can overlap.

• **Turbulence:** Extend the study of turbulent plasma transport to much larger plasmas, providing a strong test of fundamental physics scaling of turbulence.

• **Plasma-materials:** Extend the study of plasma-materials interactions to much higher power, much greater pulse length.

**Today:** Fusion power 11-17 MW for ~1 second, gain of < 1
**ITER:** 500 MW for 10 minutes, gain > 10
**Power Plant:** 2500 MW, continuous, gain > 25, ~ same size
No disruptions.
ITER will develop fusion-energy technology

- Superconducting magnets
- First wall materials
- Remote handling
- Tritium breeding blankets (at modest neutron fluence)
Princeton Plasma Physics Laboratory

- 436 FTE employees
- 20 postdocs
- 38 graduate students
- ~250 visiting scientists
  (40 resident)

$92M (FY 10)

Founded 1951
PPPL Strategic Initiatives

• Develop magnetic fusion energy
  – Advance the spherical tokamak for multiple fusion applications
  – Explore the physics and engineering science of plasmas producing fusion power (ITER & beyond)
  – Use 3D magnetic fields for steady-state, disruption-free plasma confinement
  – Develop integrated predictive models of burning plasmas
  – Develop methods to control the plasma-material interface

• Establish a center of excellence in plasma astrophysics

• Develop plasma science and related applications
National Spherical Torus Experiment

- Extremely compact tokamak; increased curvature & shearing
- Lower magnetic field strength required
- Increased efficiency, cost effectiveness
NSTX Mission Elements

- Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)
- Develop solutions for plasma-material interface
- Advance toroidal confinement physics for ITER and beyond
- Develop ST as fusion energy system
NSTX Can Study Electron-scale Turbulence

Short wavelength electron turbulence measured by microwave scattering (accessible due to NSTX weak magnetic field)

- Properties consistent with theory based on turbulence via electron temperature gradient, but
- Measured fluctuations increase with temperature (contrary to confinement scaling)
- Theory based on larger-scale ion turbulence scales as in experiment
Confinement and turbulence

- Why does the spherical tokamak scale differently with temperature than the tokamak?

Confinement time (normalized)

Favorable scaling,

$\sim v_e^{-0.97}$

$\sim$ independent of collision frequency in the tokamak

Why the difference? Will it persist?

- What determines electron turbulence and transport in toroidal plasmas? (Important for ITER confinement)
NSTX-Upgrade

new center stack

second neutral beam

Double the current, double the heating power, quintuple the plasma duration

big boost to all NSTX science missions
(parameters closer to burning plasma conditions)
The plasma-material interface challenge

- Materials to survive intense fluxes (10 MW/m², and beyond)
- Plasma survival in presence of material influence

A plasma physics and materials science challenge

In tokamaks, heat exhaust magnetically channeled to special plates

width of exhaust plume is key challenge for material survival

ITER will use tungsten
Liquid lithium boundary

- The materials benefit
  
  no erosion, neutron damage, heat overload (if flowing), self-regenerating

- The plasma confinement benefit

  highly absorbing, no cold gas in-flux, reduced transport

Liquid lithium plate
Liquid lithium boundary

• The materials benefit
  no erosion, neutron damage, heat overload (if moving), self-regenerating

• The plasma confinement benefit
  highly absorbing, no cold gas in-flux, reduced transport

NSTX
Solid lithium coating improves confinement
Broader Plasma-Material Interface program

- NSTX: liquid lithium, magnetic channeling, source of high heat flux
- Lithium Tokamak Experiment (LTX)
  exploratory tokamak with full liquid lithium surface coverage

Started liquid lithium operation in FY 11
PPPL responsibilities for ITER Construction

- Design/management of steady-state electric power network
- Management of US diagnostics contribution
- Design of diagnostic port plugs
- Conceptual design of in-vessel coils
- Various specific design tasks
3D Magnetic Shaping Provides Solutions

With 3D magnetic cage, carefully optimized, plasma is

• steady-state (no need to drive current in plasma)

• free of disruptions (no current-driven instabilities)

• high gain (no power needed for current drive)
PPPL Leading International Partnerships on 3D

- Large International Facilities, none in US

W7-X (Germany)

LHD (Japan)

W7X: trim coils, diagnostics, divertor physics/eng’g, machine assembly

LHD: diagnostics, 3D plasma analysis, transport
The road to fusion power

- ITER: ~ 2020 - 2040
- Fusion Nuclear Facility: ~ 2025 - 2040
- First of a kind Power Plant: ~ 2040

Supporting Physics and Technology:
- high performance, steady state
- Materials R&D
- Plasma Material Interface
Conceptual designs are being developed in the US and the World

Fusion Pilot Plant designs
• Address fusion nuclear technology issues, and
• Generate net electricity (requires achieving high efficiency)
• Demonstrate reliable, robust operation and maintenance

tokamak  compact tokamak  stellarator
Magnetic fusion activity is Escalating across the world

England: JET tokamak

China: superconducting tokamak EAST

Japan: superconducting stellarator

Korea: superconducting tokamak KSTAR
Major facilities under construction

Japan: superconducting tokamak JT60-S  Germany: superconducting stellarator W7-X

France: ITER
The US operates a strong set of medium-scale experiments

General Atomics: DIII-D tokamak  MIT: CMOD tokamak  PPPL: NSTX spherical tokamak

• These facilities advance critical issues for ITER and beyond

• However, the 6 major facilities overseas are more capable than the US facilities

• US contribution to the world fusion program is needed to meet the R&D challenges

• Reinvigoration of the US program is essential for US competitiveness in fusion
Summary

• Fusion research is about to enter burning plasma regime.

• Predictive understanding of high temperature plasma dynamics has been developed. ITER will validate in burning plasmas.

• Solutions to remaining challenges (steady-state, robust stability) are developing.

• World is aggressively pursuing fusion energy. US must invest to stay engaged.
16 MW in 1997

~ 10 MJ

JET, UK
The Estimated Development Cost for Fusion Energy is Essentially Unchanged since 1980

Fusion Development is on Budget.
Different Approach: Stellarators

Model A Stellarator
ca. 1953
(with Prof. Lyman Spitzer)
Progress in Fusion has Outpaced Computer Speed

Progress is paced by the construction of new facilities.
Fusion Can Deliver on a Reasonable Timescale

Estimated Total Primary Energy Consumption

World Primary Energy Consumption (TW)

Fusion with growth rate = 0.4% / year of total energy.

Needed new non-CO$_2$-emitting power. $750B / year market (today’s dollars).

ROI and Real Options analyses are very favorable.
• Many other plasma problems are three-dimensional
  – Magnetosphere; astrophysical plasmas
  – free-electron lasers; accelerators
  – perturbed axisymmetric laboratory configurations
• Development of 3D plasma physics is synergistic, with stellarator research often driving new 3D methods. Examples:
  – methods to reduce orbit chaos in accelerators based on stellarator methods [Chow & Carry, Phys. Rev. Lett. 72, 1196 (1994)]
  – chaotic orbits in the magnetotail analyzed using methods developed for transitioning orbits in stellarators [Chen, J. Geophys. Res. 97, 15011 (1992)]
  – astrophysical electron orbits using drift Hamiltonian techniques and magnetic coordinates developed for stellarators
  – tokamak and RFP resistive wall modes are 3D equilibrium issues
  – transport due to symmetry breaking was developed with stellarators
U.S. Collaboration with German Stellarator Program Shows Quiescent high-$\beta$

Stellarators make Long, Quiet Plasma Pulses
LHD in Japan: 54 minute discharges.
Plasma astrophysics

New report, initiated by PPPL, makes the case for plasma astrophysics

Describes 10 major questions in plasma astrophysics
e.g.,
• What powers the most luminous sources in the universe?
• How do magnetic explosions work?
• Can magnetic fields affect cosmic structure formation?

Describes 10 plasma processes underlying astrophysical phenomena
e.g., reconnection, dusty plasmas, radiation hydrodynamics, angular momentum transport.....

Report being conveyed to funding agencies (DOE, NASA, NSF)
Max Planck/Princeton center for plasma physics

- Proposed a joint research center between the Max Planck Society (Germany) and Princeton

- Selected topics in fusion and plasma astrophysics

- Germany: Institute for Plasma Physics (Garching, Greifswald)
  Institute for Astrophysics (Garching)
  Institute for Solar System Research (Lindau)

  US: PPPL
  Princeton Department of Astrophysical Sciences

- Approved in Germany (supporting 12 German postdocs), contingent on US funding

- Proposed to DOE (6.5 postdocs), NSF (3 postdocs, J. Stone), Princeton (funding 2.5 postdocs)