Magnetic Fusion Energy: Status and Opportunities

Prof. Robert J. Goldston, Director
Princeton Plasma Physics Laboratory

Presentation to:
Secretary of Energy Advisory Board
Task Force on Fusion Energy

March 29, 1999
OUTLINE

• Fusion, Why and When?
• The Plasma Science of Magnetic Fusion
• The Magnetic Fusion Energy Portfolio
• Science and Technology Spin-offs
• Summary and Recommendations
Why Fusion Energy?

- **Abundant Fuel, Available to All Nations**
  - Deuterium and Lithium

- **Environmental Advantages**
  - No Carbon Emissions
  - Low Radioactivity

- **Can’t Blow Up, Can’t Melt Down**
  - < 5 Minutes of Fuel in Plasma

- **Low Risk of Nuclear Materials Proliferation**

- **Concentrated Relative to Solar, Wind, Etc.**
  - Minimal Land Use

- Not subject to daily, seasonal or regional weather variation.
  - No Need for Massive Energy Storage
  - No Need for Long Distance Transmission

Magnetic Fusion Energy
Environmental Attractiveness of Fusion

Comparison of Fission and Fusion Radioactivity after Shutdown

Magnetic Fusion Energy
Japan and Europe Are Pressing Forward Aggressively with Magnetic Fusion Energy

- Japan and Europe have less energy resources than U.S., and greater concern about dependence on foreign energy supplies.
  - Japanese MFE Budget ~ 1.5 x U.S.
  - European MFE Budget ~ 2.5 x U.S.
- Japan and Europe are continuing the ITER Engineering Design Activity.
- Japan and Europe each are operating or constructing:
  - A ~$1B class tokamak experiment
  - A ~$1B class superconducting stellarator experiment.
- The U.S. now has no device in the ~$1B class.
A Different Kind of Energy Economy will be Needed in the Future

- 3x more energy
- 3x less CO2 emissions

' Climate Change 1994, IPCC
PPPL#98GR008

Magnetic Fusion Energy
NEW FUSION PROGRAM STRATEGY

Advance in Large-Scale Fusion Energy Technology

- Portfolio of innovative concepts, including inertial fusion energy
- Broader scientific areas of inquiry
Fusion Energy Science Sits in *Pasteur’s Quadrant*

**The Grand Challenge:**
Excellent basic scientific understanding enabling the innovations that will make fusion energy practical.
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• Summary and Recommendations
Schematic of MFE Power Plant

Plasma Confinement and External Heating

Magnet

Blanket

Raw Fuel

Li

D

First Wall

Balance of Plant

Energy / Fuel Recovery

Fuel

Waste

\( Q_p \)

\( \eta_R P_E \)

\( P_E \)

Magnetic Fusion Energy
Toroidal Confinement

Magnetic Confinement

Magnetic Fusion Energy
PLASMA SCIENCE AREAS IN MFE

- Macroscopic Stability
- Wave-particle Interactions
- Transport and Microturbulence
- Plasma-wall Interactions
FUSION POWER IS DETERMINED BY MACROSCOPIC STABILITY

- Plasma stability is largely determined by

\[ \beta \equiv \frac{2nT}{B^2 / 2\mu_0} \]

- Fusion power

\[ p_{\text{fus}} = E_{\text{fus}} n_d n_t \left\langle \sigma_{\text{fus}} v \right\rangle \sim n^2 T^2 \sim \beta^2 B^4 \]

- Denser, hotter plasma makes more fusion.

Magnetic Fusion Energy
Ideal MHD Theory Provides Accurate Guidance on Operational Boundaries in Tokamaks

- Plasma shaping enables increasing $I/aB$ and the $\beta$-limit.
- Elongation - $\kappa$
- Triangularity - $\delta$
- Inverse aspect ratio $\varepsilon = a/R$

- Violation of $I/aB$ or $\beta$ limits results in sudden "disruptions".

Magnetic Fusion Energy
Small Spherical Torus in U.K. Reached Record (~40%) Average Toroidal $\beta_t$
WE KNOW WE CAN MAKE FUSION ENERGY –
THE CHALLENGE NOW IS TO MAKE IT PRACTICAL

Progress in Fusion Energy

Magnetic Fusion Energy
Wave-Particle Interactions are Critical for Plasma Sustainment

- Plasma heating and current-drive
  - By beams of energetic neutral atoms
  - By radio-frequency waves

- Plasma self-heating by $\alpha$ particles

- Discovery of the “bootstrap” current has revolutionized toroidal systems.
Plasma heating by neutral atom injection is effective and well understood.
**Confined Alphas in the Plasma Core Show Classical Slowing Down Spectrum**

- **TRANSP calculation includes:**
  - orbit trajectories
  - classical slowing down
  - time dependence of alpha production

\[
\text{Double Charge Exchange Technique: } \text{He}^{++} + \text{Li}^+ \Rightarrow \text{He}^0 + \text{Li}^{3+}
\]

\[
\text{TRANSP/FPPT normalization}
\]

\[
\text{Alpha energy (MeV)}
\]

\[
\text{dn/dE (a.u.)}
\]

\[
\text{V}_\text{pellet}
\]

\[
\text{Li}
\]

\[
\text{He}^0 \text{ Cloud}
\]

\[
\text{He}^{++} \text{ Alpha Particles}
\]
Neo Classical Theory Prediction of Bootstrap Current Confirmed

- Plasma surface voltage is well modeled by including beam-driven and bootstrap currents.
- Enabled design of Advanced Tokamak, Spherical Torus, and Stellarator.

*Magnetic Fusion Energy*
Theory successfully predicts island widths for low $m/n$ neo-classical modes.

- Inhomogeneities in bootstrap current can be self-reinforcing.
- In stellarators, bootstrap current can be self-stabilizing.
Fusion Gain is Determined by Transport and Microturbulence

- Fusion power density
  \[ p_{fus} = E_{fus} n_d n_t \langle \sigma_{fus} v \rangle \sim n^2 T^2 \]

- Heat loss
  \[ P_{loss} \equiv \frac{3nT}{\tau_E} \]

- Turbulence should not let heat out faster than it can be produced.
**Confinement Is Predictable**

![Graph showing confinement data for various tokamaks with RMSE=15.3%](image)

- TCV
- PDX
- PBX-M
- JT-60U
- JFT-2M
- JET
- DIII-D
- COMPASS-D
- ALCATOR C-Mod
- ASDEX Upgrade
- ASDEX

**Magnetic Fusion Energy**
ION TURBULENCE CAN BE ELIMINATED

\[ \chi_{i}^{\text{tot}} = \frac{Q_i}{n_i} \nabla T_i \]
**Gyrokinetic Theory**

- Simulations show turbulent eddies disrupted by strongly sheared plasma flow

**Experiment**

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

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**Magnetic Fusion Energy**
Plasma-Wall Interactions are Critical to Fusion Power Density

• 20% of DT fusion power is emitted as radiation and particle flow to the first wall.

• The heat and particle flows are concentrated in space by plasma divertors, and in time by plasma disruptions.

• Major advances have been made recently in learning to control plasma-wall interactions.
MAGNETIC DIVERTOR CHANNELS BOTH HEAT AND PARTICLES

- Directs heat flux away from plasma boundary.
- Permits pumping of neutral helium ash.
Neutral Particle Concentration
AIDS Ash Removal & Heat Reduction

- Plasma is extinguished by recombination.
- Heat flux is greatly reduced.
- Disruption mitigation is an active research area.
THE ROLE OF COMPUTATION

• Plasma physics is governed by Maxwell’s equations and the Lorentz force equation.

• Powerful Particle-in-Cell (PIC) codes examine microturbulence and transport.

• Powerful fluid codes examine macrostability.

• Advanced simulation will accelerate the cycle of theoretical understanding and experimental innovation.
Realistic Simulations Enabled by New MPP

3D nonlinear gyrokinetic simulations: flow suppression of turbulent transport

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MHD Simulation of $n=1$ Tilting Instability in FRC
PIC Codes Scale Well to Massive Parallelism

![Graph showing the scalability of PIC codes across different processors.](image)

- **Y-axis**: The number of particles which move 1 step in 1 second

**Legend**:
- T3E
- Origin 2000
- Cray-C90
- Cray-J90

**Magnetic Fusion Energy**
OUTLINE

• Fusion, Why and When?

• The Plasma Science of Magnetic Fusion

• The Magnetic Fusion Energy Portfolio

• Science and Technology Spin-offs

• Summary and Recommendations

Magnetic Fusion Energy
KEY IDEAS BEHIND THE PORTFOLIO APPROACH

• Strong scientific synergy – Commonality
  – Ideas from one configuration help others
  – Hybrid configurations emerge

• Breadth – Complementarity
  – Avoids common roadblocks
  – Broadens Science and Technology spin-offs

• Leverage off >$1B/year International Program
MFE Configurations in the Portfolio

Externally Controlled
- Stellarator
  - Coils link plasma
  - Magnetic fields from external currents
  - Toroidal field >> poloidal field
  - Large R/a
  - More stable, better confinement

Self Organized
- FRC
  - Coils do not link plasma
  - B from internal currents
  - Poloidal B >> Toroidal B
  - R/a → 1.0
  - Higher power density

Magnetic Fusion Energy
STAGES OF DEVELOPMENT

- **Concept Exploration**
  Ideas are given their first test, at a small scale.

- **Proof of Principle**
  First integrated tests of confinement, stability, sustainment, plasma-wall interactions.

- **Performance Extension**
  Plasma parameters approach power plant conditions – test scaling, new physics.
Roadmap to Attractive Fusion Power — A Portfolio Approach —

Attractive Commercial Fusion Power Plant

DEMO

Fusion Energy Development

Performance Extension

Proof of Principle

Concept Exploration

Technology & Materials, Theory and Advanced Simulation

Technology & Materials, Theory and Advanced Simulation

Technology & Materials, Theory and Advanced Simulation

New Concepts

Decision Criteria

Economically and environmentally attractive electricity production demonstrated; reliability and cost data sufficient for commercial exploitation.

Scientific and technological feasibility demonstrated; Environmental attractiveness demonstrated.

Physics basis verified in energy-relevant regime; technology requirements established; attractive power-plant features.

Physics basis established; Energy implementation attractive.

Physics shown to be promising; Energy vision attractive.

Ongoing Decisions: 1999 and later

Next Decisions: 2004 and later

Magnetic Fusion Energy
**THE TOKAMAK IS THE MOST ADVANCED CONFIGURATION IN MFE**

- Stable operation
- Good confinement
- Excellent database supporting other MFE configurations.

**Issues:**
- Modest power density
- Continuous operation impractical
- Disruptions
PROGRESS IN TOKAMAK PERFORMANCE HAS BEEN DRAMATIC

Magnetic Fusion Energy
Joint European Torus (JET)
THE ADVANCED TOKAMAK RESOLVES KEY TOKAMAK ISSUES

• Features:
  – High bootstrap current reduces power requirement for steady-state current drive.
  – Hollow current profile allows high-beta stability to short-wavelength modes.

• Areas of research:
  - Stability to long-wavelength modes.
  - Current and pressure profile control.
The Advanced Tokamak Leads to an Attractive Fusion Power Plant

- **THE 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

Magnetic Fusion Energy
ST Maximizes the Good-Curvature Field Line Length over the Bad-Curvature Field Line

This leads to very high $\beta$ and widens ST parameter domain.
Magnetic Fusion Energy
A World-Class Innovative Fusion Experiment

Baseline Parameter

- Major radius $\leq 85 \text{ cm}$
- Minor radius $\leq 68 \text{ cm}$
- Plasma current 1 MA
- Toroidal field 0.3–0.6 T
- Heating and current drive 11 MW
- Flat-top time 5–1.6 s

Magnetic Fusion Energy
ST Can Advance Fusion Science and Technology Using Small-Size Devices

Neutron Fluence (MW-a/m²) per Year
Advance in Fusion Energy

Magnetic Fusion Energy
Japanese LHD Stellarator Has Begun Operation

Magnetic Fusion Energy
U.S. Program: Compact Stellarators

• Revolution in theoretical understanding plus tokamak experimental results allows numerical design of attractive stellarator configurations.
  - Excellent plasma confinement.
  - High $\beta$ stability.
  - Design to stabilize troubling instabilities.
    E.g. kink and neoclassical tearing -- modes.

• Can combine physics advances observed in tokamaks with stellarator flexibility $\rightarrow$ more compact designs.
  - Current stellarators have high aspect ratios, $R/a \sim 8 - 11$.
  - Can get $R/a \sim 2 - 4$ using bootstrap current.
    $\Rightarrow$Reduce size and cost of experiments, reactors.
NCSX: NATIONAL COMPACT STELLARATOR EXPERIMENT

- \( R/<a> = 3.4, \)

- **THEORETICALLY:**
  \( \beta \geq 4\% \) STABLE TO BALLONING, NEO-TEARING.
  
  STABLE TO EXTERNAL KINK WITHOUT CONDUCTING WALL, ROTATION, OR FEEDBACK \( \Rightarrow \) SIMPLER.

- **EXPERIMENT:** TEST STABILITY, IMMUNITY TO DISRUPTIONS.

- **PROPOSAL:** BUILD RE-USING COMPONENTS OF AN EXISTING TOKAMAK.
The compact stellarator could combine the best features of tokamaks and stellarators.
Reversed Field Pinch (RFP) Magnetic Configuration

- toroidal field $B_T$ ≈ poloidal field $B_P$
- large "magnetic shear" (field line twists >90° from center to edge)
Magnetic Fluctuations Drive Poloidal Current in a Reversed Field Pinch

Good agreement is obtained between theory and experimental measurements of the dynamo mechanism.
The Reversed Field Pinch

• Key power plant advantage:
  - Weak magnetic field
  - (RFP ≈ tokamak with field reduced 10x)

• Physics consequence:
  - Strong magnetic turbulence
  - Large energy transport

• Possible solution:
  - Eliminate energy source for turbulence
  - Control current profile

• Initial results encouraging
  - Five fold confinement gain

• Proposal to increase diagnostics, current drive, plasma heating: concept exploration → proof of principle
Reversed Field Pinch
Elements of MTF

Plasma preheater and injector

Liner implosion system

Typical parameters:

<table>
<thead>
<tr>
<th></th>
<th>Initial</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n)</td>
<td>(10^{17}) cm(^{-3})</td>
<td>(10^{20}) cm(^{-3})</td>
</tr>
<tr>
<td>(T)</td>
<td>300 eV</td>
<td>10 keV</td>
</tr>
<tr>
<td>(B)</td>
<td>100 kG</td>
<td>10 MG</td>
</tr>
</tbody>
</table>

Magnetic Fusion Energy
MAGNETIZED TARGET FUSION OFFERS SIGNIFICANT YIELD AT LOW COST

- Fuel density and time scale are intermediate between MFE and IFE; magnetic field is high.
  ⇒ Smaller than MFE, lower power than IFE.
- Can use pulsed-power Defense facilities that exist or are under construction.
  ⇒ $B$ class facilities are not required for $Q=1$.
- Broadens scientific boundaries of MFE and IFE.
- Issues include stand-off and rep-rating, ultimate gain limitations in the absence of a "hot-spot."

Magnetic Fusion Energy
## Science Topics vs. Configurations

### External Controlled vs. Self-organized

<table>
<thead>
<tr>
<th>Topic</th>
<th>Configurations</th>
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</thead>
<tbody>
<tr>
<td><strong>MHD: Stability, Reconnection, &amp; Dynamo</strong></td>
<td>Stellarator, Compact Stellarator, Tokamak, Advanced Tokamak, Spherical Torus, Reversed Field Pinch, Spheromak, Field Reversed Configuration</td>
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<tr>
<td></td>
<td>n=1 mode control with wall</td>
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<tr>
<td></td>
<td>Tearing mode control</td>
</tr>
<tr>
<td><strong>Transport &amp; Turbulence</strong></td>
<td>Stellarator, Compact Stellarator, Tokamak, Advanced Tokamak, Spherical Torus, Reversed Field Pinch, Spheromak, Field Reversed Configuration</td>
</tr>
<tr>
<td></td>
<td>Turbulence suppression - control of transport</td>
</tr>
<tr>
<td><strong>Wave Particle Interaction</strong></td>
<td>Stellarator, Compact Stellarator, Tokamak, Advanced Tokamak, Spherical Torus, Reversed Field Pinch, Spheromak, Field Reversed Configuration</td>
</tr>
<tr>
<td><strong>Heating &amp; Current Drive</strong></td>
<td>Stellarator, Compact Stellarator, Tokamak, Advanced Tokamak, Spherical Torus, Reversed Field Pinch, Spheromak, Field Reversed Configuration</td>
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<tr>
<td></td>
<td>Bootstrap current</td>
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<td></td>
<td>Helicity injection</td>
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<td></td>
<td>Rotamak current drive</td>
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<tr>
<td><strong>Plasma Wall Interaction</strong></td>
<td>Stellarator, Compact Stellarator, Tokamak, Advanced Tokamak, Spherical Torus, Reversed Field Pinch, Spheromak, Field Reversed Configuration</td>
</tr>
<tr>
<td></td>
<td>Divertor</td>
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</table>

- Range of devices where issue is significant
- Major studies being carried out in international program

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**Magnetic Fusion Energy**
Present and Proposed U.S. MFE Portfolio

Attractive Fusion Energy Source

- Fusion Energy Development
  - Performance Extension
    - Proof of Principle
      - Concept Exploration
        - Advanced Stellarator
        - Advanced Tokamak
        - Spherical Torus
        - RFP, FRC Spheromak
        - Emerging

- Cost

* = Proposed

Fusion Technology & Plasma Theory

Magnetic Fusion Energy
THE TOKAMAK / AT IS TECHNICALLY PREPARED FOR A HIGH-GAIN TEST

• The 3 ITER partners could decide (yes/no) on construction any time between 2001 – 2003.

• The U.S. should consider requesting LHC-like participation if the decision is yes.

• The U.S. should prepare alternative international approaches if ITER will not go forward.

Magnetic Fusion Energy
THE REDUCED-COST ITER HAS ADVANCED TOKAMAK FEATURES
A LIMITED-PULSE ADVANCED TOKAMAK BURNING PLASMA DEVICE SHOULD COST ~ $1B

Design Goals

- $R = 2.0\ m$, $a = 0.525\ m$
- $B = 10\ T$
- $I_p = 6.5\ MA$
- $P_{\text{fusion}} \sim 220\ MW$
- $Q \sim 10$, $\tau_E \sim 0.55s$
- Burn Time $\sim 10s$
- Total Project cost $\sim $ 1B
ENABLING TECHNOLOGIES FACILITATE EXPERIMENTAL RESEARCH

- Experimental research paced by availability of tools.

• Some key areas:
  - Plasma heating and current drive
  - Fueling
  - Power handling
  - Plasma diagnostics

1MW 110 GHz gyrotron with CVD diamond window for long-pulse electronic cyclotron resonance heating, developed through U.S. MFE Program

Magnetic Fusion Energy
FUSION TECHNOLOGIES POINT TO INNOVATIVE APPROACHES

Flowing Liquid Wall Spherical Torus

• Flowing liquid walls may permit very high fusion power density.
• Wall-protection reduces need for low-activation structural materials.

Magnetic Fusion Energy
• IMPACT PROPERTIES OF VANDIUM ALLOY ARE UNAFFECTED BY EXPOSURE TO TOKAMAK ENVIRONMENT.
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Some Science Spinoffs of Fusion

MAGNETIC RECONNECTION

ATOMIC PHYSICS OF LINE RADIATION—IRON SPECTRUM
X-RAY CRYSTAL SPECTROMETER

STUDY OF SOLAR WIND EFFECTS

Magnetic Fusion Energy
Some Technology Spinoffs of Fusion

CHIP PROCESSING

HALL THRUSTER

FLAT PANEL DISPLAY

ARC FURNACE

Magnetic Fusion Energy
Education

- Science outreach to K-12 teachers and students nationally.
- National Undergraduate Fellowship Program 30 students/yr.

Graduate Education

- 35 Research Universities involved in fusion research.
- Estimate >750 Ph.D’s awarded.
• Fusion, Why and When?
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Summary of Status

- Dramatic advances have been made in all areas of fusion Plasma Science:
  - Macroscopic Stability
  - Wave-particle Interactions
  - Transport and Microturbulence
  - Plasma-wall Interactions

- A portfolio of synergistic and complementary confinement experiments is in place.
2003 – 4 WILL PRESENT OPPORTUNITIES

• The decision could be taken to construct an Advanced Tokamak burning-plasma experiment.

• The Spherical Torus could advance to Deuterium – Tritium Performance Extension.

• The new Proof of Principle experiments may show attractive paths forward.

• Existing Concept Exploration experiments may be ready to move to Proof of Principle.

Magnetic Fusion Energy
To Prepare for Decisions in 2003-04 will require additional funds

- All existing facilities are underutilized.
- New PoP experiments require funding.

- **This new fusion roadmap provides the programmatic basis for increased support for fusion energy research.**
Conclusions and Recommendations

- MFE research is making excellent progress, based on a synergistic portfolio approach.

- There are important opportunities for investment in MFE (and IFE).

- A budget increase to $300M/year
  + $40M in MFE
  + $40M in IFE
would prepare both programs to move forward aggressively, if the Nation so chooses, in 2003-4.

*Magnetic Fusion Energy*
“The road to useful power from fusion may be a long one, but the commanding importance of the goal continues to arouse strong commitments.”

“...the effort is to reach that plateau which the theorists have held out to us of high confinement under high temperature and relatively undisturbed conditions. ... I have the impression that the promised land is virtually within sight. And on that basis one can be intelligently optimistic about the future, as I think many of us are.”

Dreams, Stars, and Electrons, 1997
Lyman Spitzer, Jr.
Jeremiah Ostriker

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