Update of Magnetic Fusion Energy Research

Brian A. Nelson
for the UW Fusion Energy Research Group
University of Washington
(Some slides stolen from General Atomics web site, fusion.gat.com)
nelson@ee.washington.edu

University of Washington Energy and Environment Seminar
October 23, 2008
Fusion is the *Ultimate* Energy Source

- Existing energy sources are less attractive:
  - Fossil fuels are being depleted; greenhouse gases
  - Hydro power is getting more difficult to implement
  - Nuclear power not (yet) growing; disposal concerns

- Solar, wind, geothermal, tide, *etc.* have limited power output and location capabilities

- Fusion has no greenhouse gases, doesn’t flood valleys, has short-lived radioactivity, and works at night in Nebraska on a calm day. Fuel supply is estimated to last 5 million years.
Outline

1. Fusion: Why, What, and How
   - Fusion Reactions
   - Methods for Producing Fusion
   - Advantages of Fusion (and Short History)

2. Fusion Research Progress
   - Tokamaks
   - Alternative Concepts
   - UW Fusion Research

3. Summary
First Generation of Man-made Fusion will be D – T

- Deuteron
- Energetic Neutron
- Triton
- Helium Nucleus

Fusion Reaction
Large Energy Output from Mass “Loss” of Products

- Fraction of mass converted to energy is 30 parts of 10,000
- 1 gram of DT is energy equivalent of 2400 gallons of oil

\[ E = mc^2 \]
There are Three Methods of Producing Fusion:

1. Magnetic Confinement
   - Nucleus
   - Electron
   - Magnetic Field

2. Intense Energy Beams
   - Fuel Pellet

3. Gravitational Confinement
   - SUN
   - Inertial Confinement
Fusion’s Three Ingredients: The Lawson Criterion

Thermonuclear fusion criterion for energy breakeven:

\[ n\tau_E > 3 \times 10^{20} \text{ m}^{-3}\text{s} \]

at \( kT = 15 \text{ keV} \)

- **Density** \( n \)
  - Enough particles to fuse

- **Temperature** \( kT \)
  - High temperature for particles to fuse

- **Energy confinement time** \( \tau_E \)
  - Energy isn’t lost too quickly
Fusion Reactions are Heater for Steam Cycle
Fuel Usage: Fusion is the Highest Energy Density

- Coal: ~2,000,000 tonnes (21,010 railcar loads)
- Oil: ~1,300,000 tonnes (10,000,000 barrels)
- Fission: ~30 tonnes UO₂ (one railcar load)
- Fusion: ~0.6 tonnes D (one pickup truck)
Brief History of Fusion Energy Research

- 1951: Argentina’s dictator, Juan Peron, funds fusion research on remote island, soon announces complete success! (Never heard from again . . .)
  - Starts US fusion energy research
- 1953: US Project Sherwood established (classified fusion energy research)
- September 1958: Project Sherwood declassified (2nd Atoms for Peace Conference, Geneva), fusion research becomes open worldwide
- Late 1960’s: Soviet announcement of \( T_e \sim 200 \text{ eV} \) in “tokamak” (2 million degrees K)
  - Artsimovich tours US and convinces many; Princeton bets measurement is wrong
  - US delegation visits Moscow, verifies high temperatures . . .
  - Princeton loses the bet . . .
- Early 70’s: tokamaks at every major lab in the world
Best Results Have been from Tokamaks

Toroidal field for stability
Poloidal field for confinement – (requiring current drive)

Toroidal field is expensive
Largest US Tokamak: DIII-D at General Atomics
DIII-D (Plasma on Left Side)
World’s Largest Tokamak: JET in the UK

B A. Nelson et al.
Next Tokamak Project: ITER in France

The International Thermonuclear Experimental Reactor
Fusion Progress has Outpaced Moore’s Law

FUSION POWER

- 1,000
- 100
- 10
- 1


PLT Princeton Large Tokamak
PDX Princeton Director Experiment
JET Joint European Torus
DIII & DIII-D General Atomics Tokamak Experiments
TFTR Princeton Plasma Physics Laboratory
ALCATOR C Massachusetts Institute of Technology
ITER International Thermonuclear Experimental Reactor
JT-60U Japanese Tokamak Experiment
Fusion Ain’t Easy or Cheap
Improvements are being Sought

- Present reactor designs are large (2 GW+) and complex:
  - Activation of reactor itself
  - More expensive cost of electricity

- Need higher plasma pressure and lower magnetic field
  \[ \beta \equiv \frac{nkT}{(B^2/2\mu_0)} \]

- Need an efficient steady-state current drive
“Compact Toroids” have a *Huge* Reactor Advantage

- Optimum $a \sim 3 \text{ m}$
  $\sim$ blanket + shield + coils
- Reactor cost $\propto area$
- Compact reactor cost down by $\sim 10$
Alternate Path to Commercial Reactor is Cost Effective

Two paths to fusion power

ITER

Device cost

ITER-tokamak

Spheroidal (CT)

Performance

Burning plasma

DEMO

B A. Nelson et al.  Fusion Update
“Alternate” and “Innovative” Confinement Concepts
“ICC”s pursued at the University of Washington

- Tokamak improvements:
  - Higher $\beta$: Spherical torii (lower aspect ratio)
  - Efficient steady-state current drive

- Alternate concepts, higher $\beta$, “simply-connected”:
  - Spheromak
  - Flow shear stabilized Z-pinch
  - Field-reversed configuration (FRC)

- Computational predictability
  - Improve simulations of alternates
  - Help design of future experiments
The UW has an Active Fusion Research Program

- The Helicity Injected Torus (HIT) program
  - Tokamak improvements; current drive/low aspect ratio (collaboration with NSTX at Princeton)
  - Steady inductive spheromak (HIT–SI)

- The ZaP experiment
  - Sheared-flow stabilization of a Z-pinch

- Redmond Plasma Physics Laboratory, RPPL
  - Field-reversed configuration translation, sustainment and confinement (TCS–U)

- Plasma Science and Innovation (PSI-)Center
  - Computational predictability
  - Support for ICC experiments
Helicity Injected Torus, Steady Inductive, Spheromak

HIT–SI has achieved DC spheromak from AC drive

Achieved \( I_{\text{tor}} = 1.5 I_{\text{inj}} \)

Goal \( I_{\text{tor}} = 5 I_{\text{inj}} \)
AC Drive Produces a DC Spheromak by Relaxation

Powered by 56 IGBT H-bridge PWM SPAs, 1500 A / 900 V

\[ V_{\text{inj}} \text{ (V)} \]
\[ \psi_{\text{inj}} \text{ (mWb)} \]
\[ I_{\text{inj}} \text{ (kA)} \]
\[ I_{\text{tor}} \text{ (kA)} \]

Time (ms)
Z-Pinches Confine Plasma with Azimuthal Fields
Flow Shear Stabilizes via Phase-Mixing

Stability studies show stabilization of "kink" mode with sufficient radial shear in the axial flow ($dv_Z/dR$)

Non-linear simulations:

- No shear

$v_Z = 0$ on axis/50 km/s at wall
Coaxial Source Creates Stable Z-Pinch

ZaP Results:

Z-pinch current

Normalized mode data

Stabilized with sheared-flow over 2000 growth times
Another Compact Toroid Approach: The FRC

Simple geometry: **NO TOROIDAL FIELD**

High $\beta$ compact toroid
FRC Translation Confinement and Sustainment
The TCS–U Experiment at the UW RPPL

Separate formation, heating, and sustainment regions
Plasma Science and Innovation Center Improves Computational Predictability for ICCs

• PSI-Center developing computer codes to predict behavior of fusion experiments
• Collaboration with Caltech, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, M.I.T., Swarthmore College, Univ. Wisc., and Utah State Univ. (12 experiments)
• Only Center concentrating on smaller experiments
Summary

- Fusion energy:
  - Has energy rich, abundant fuel
  - "Cleaner" than coal and fission

- Fusion energy research has made tremendous progress

- Innovative confinement concept research is working toward more affordable reactors

- UW is a leader in research of alternate/innovative concepts

Feel free to contact me:

nelson@ee.washington.edu
(206) 543–7143