

Faith, Fusion Energy, and Federal Service

James W. Van Dam

68th Annual Meeting of the American Scientific Affiliation July 20, 2013, Nashville, TN



"But God, who is rich in mercy, out of the great love with which he loved us, even when we were dead through our trespasses, made us alive together with Christ (by grace you have been saved) ... For we are his workmanship, created in Christ Jesus for good works, which God prepared beforehand, that we should walk in them." (Ephesians 2:4-5,10, RSV)



Foundations of faith in Jesus Christ as my Lord and Savior

Christian upbringing

Family, church, Sunday School, catechism

Christian education

Kalamazoo Christian Schools K-12, Calvin College



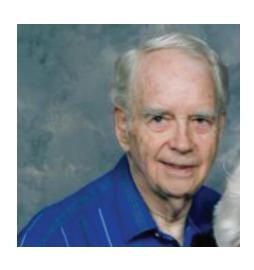
Grace Chr Ref Church

Christian conversion

- "But now is Christ risen from the dead, and become the first fruits of them that slept." (I Cor 15:20, KJV)
- <u>"Basic Christianity"</u> by John Stott
- "Come close to God and he will come close to you. Realize that you have sinned and get your hands clean again. Realize that you have been disloyal and get your hearts made true once more. As you come close to God you should be deeply sorry, you should be grieved, you should even be in tears ... You will have to feel very small in the sight of God before he will set you on your feet once more." (James 4:8-10, Phillips)



Influence of Prof. Donald DeGraaf



Source: Missions on the Frontline web site

Professor of Physics

University of Michigan-Flint, 1956-1990

Author

- What's Right? What's Wrong? Questions of Christian Conduct (Inter Varsity, 1981)
- The Physical University (Crystal Press, 1981)

Critical conversation (1967)

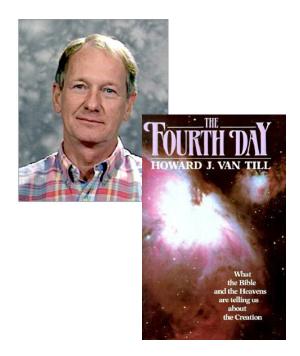
- "When the Son of Man comes in his glory, and all the angels with him, he will sit on his glorious throne. All the nations will be gathered before him, and he will separate the people one from another as a shepherd separates the sheep from the goats. He will put the sheep on his right and the goats on his left." (Matthew 25:31-33, NIV)
- Retired, but active in Missions on the Frontline



Physics professors at Calvin College



Source: U.S. Congress



Prof. Vernon Ehlers

- Experimental atomic physics (Ph.D., Berkeley)
- U.S. Congressman (1993-2011)

Prof. Roger Griffioen

38 years at Calvin: Professor, Chair, and Dean

Prof. Albion Kromminga

- Theoretical nuclear physics
- Member of ASA

Prof. Clarence Menninga

- Professor of Geology & Physical Science
- Member of ASA
- Author of several books on relationship of science and religion

Prof. Howard Van Till

- Solid state physics, astronomy
- Member of ASA (served on Exec Council)
- Author of several books on relationship of science and religion (e.g., creation/ evolution)

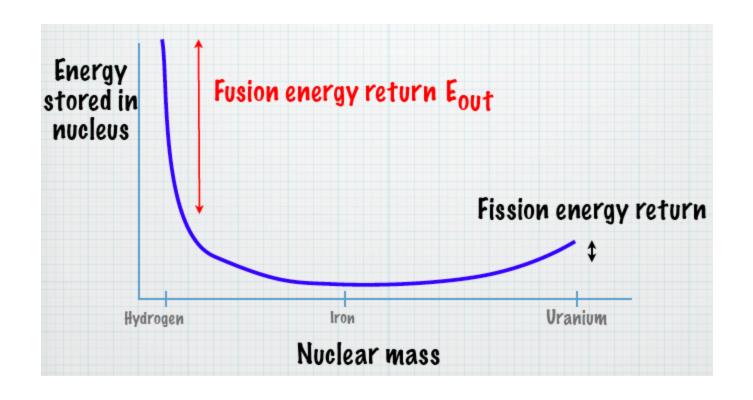
Prof. John Van Zytveld

- Calvin College (1968-1996)
- M.J. Murdock Charitable Trust senior program director for science education and research (1996-2009)



What is fusion?

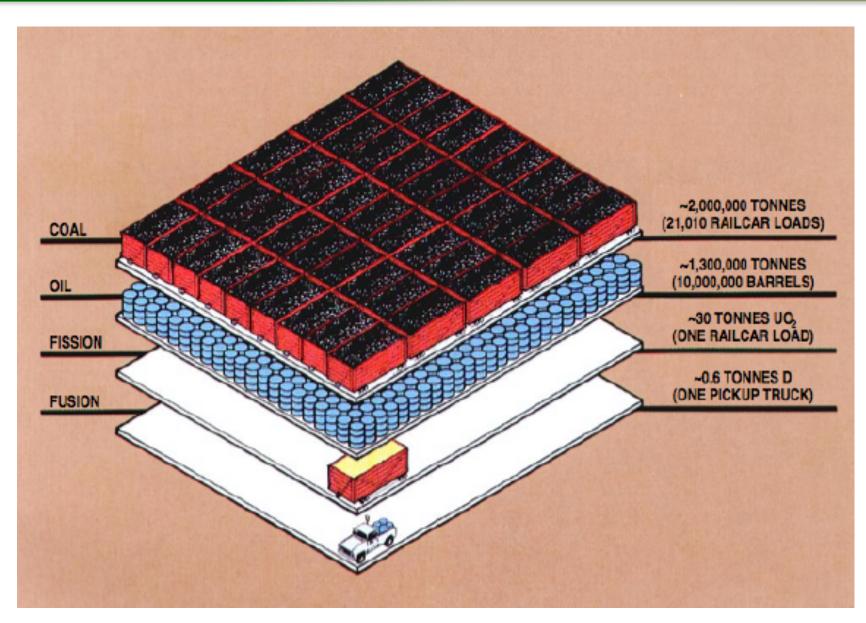
Fusion =
combination of
light nuclei to
create a heavier
nucleus and
release nuclear
energy



"But the day of the Lord will come as a thief in the night, in which the heavens will pass away with a great noise, and the elements will melt with fervent heat; both the earth and the works that are in it will be burned up." (II Peter 3:10)



Disparity of energy output

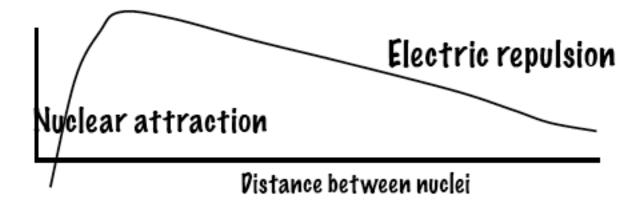




To fuse, atomic nuclear must collide at high energy

Forces:

- Electric force is repulsive and long-range; all nuclei have positive electric charge and therefore repel each other
- Nuclear force is strongly attractive, but very short range



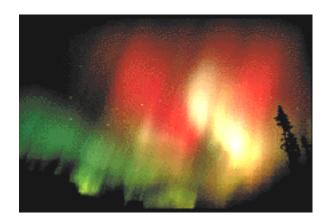
- High energy is required (hotter than the core of the Sun)
 - At these high temperatures, atomic electrons break free from their nuclei
 - Gas becomes a collection of charged particles ("plasma")
 - Plasma is sometimes called "4th state of matter"

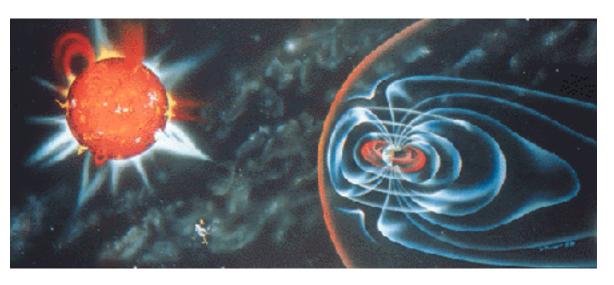


Where do plasmas occur?

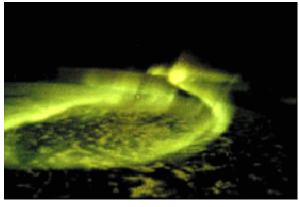
Earth:

- Magnetosphere
- Lightning bolts
- Fluorescent lights
- Aurora





Sun: ball of plasma, powered by fusion reactions

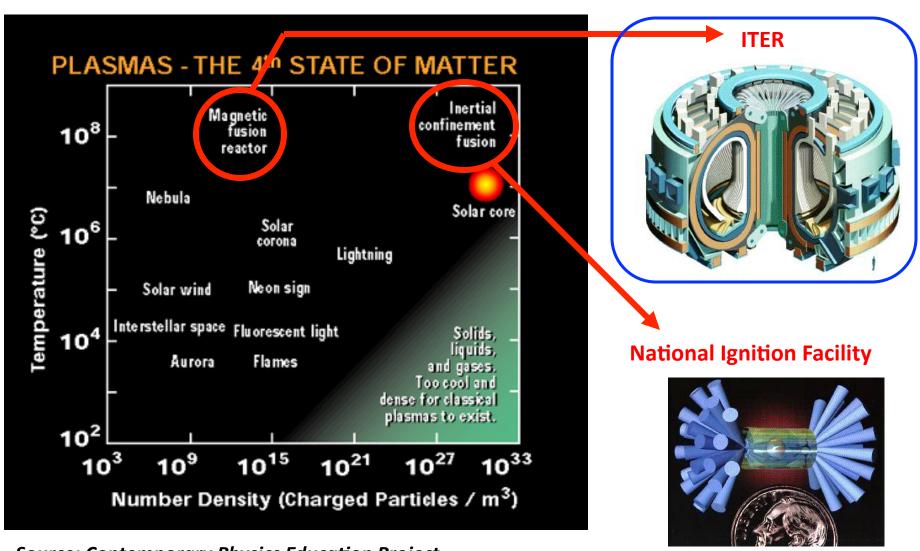


Universe:

- Atmosphere & interior of stars, supernovae, and quasars
- Interstellar and galactic space



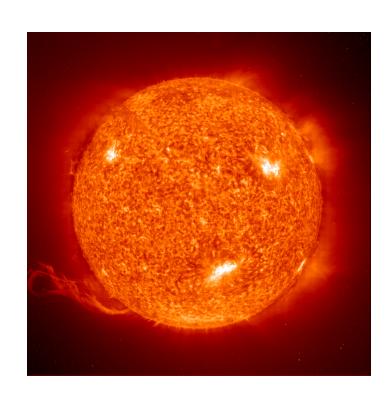
The pervasive plasma state



Source: Contemporary Physics Education Project



Wide applicability of plasma science



Makes use of: mechanics, E&M, stat mech, relativity, numerical analysis, quantum mech, solid state, AMO, math physics, ...

- Low-temperature plasmas
- Magnetosphere, solar, & astrophysical plasmas
- Geophysical fluid dynamics
- Laser interactions
- Meta-materials, photonics
- High-performance computing
- Nonlinear dynamics
- Nuclear engineering
- Plasma medicine
- Fusion energy



Confinement of fusion plasma

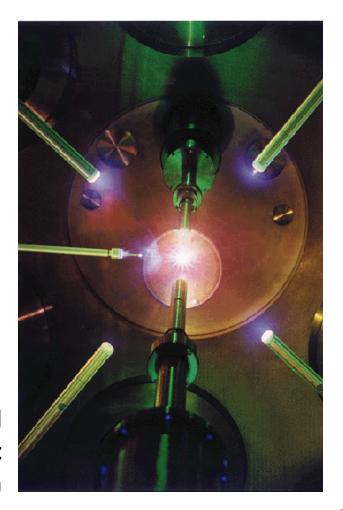
Scientists have taken two main approaches to producing fusion plasmas to explore the behavior of matter at extreme conditions.



Magnetic confinement fusion

Plasma can also be confined by **gravity**, but only on the stellar scale (e.g., the Sun), which is impractical on Earth.

Inertial confinement fusion



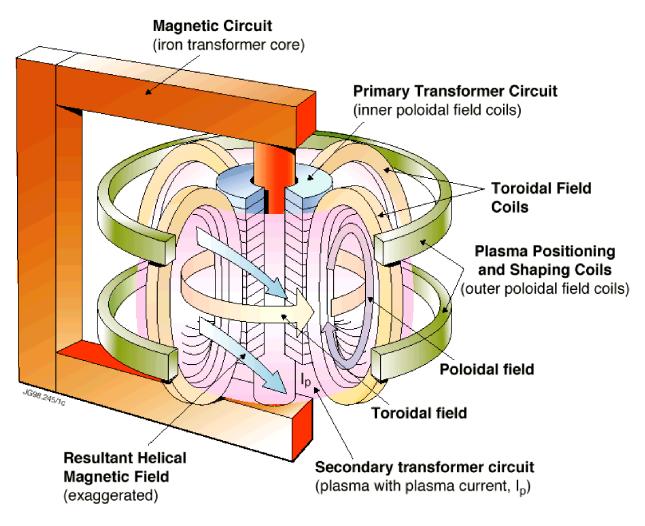




Tokamak ("toroidal magnetic chamber") is the leading magnetic confinement device

The Tokamak:

- Operationally, is essentially an electrical transformer
- Toroidal magnetic field is produced by external magnetic field coils
- Plasma current produces poloidal magnetic field
- Result is a set of nested helical surfaces
 ⇒ plasma confinement





Advantages of fusion energy

- Worldwide availability of low-cost fuel, billion-year supply
- No greenhouse-gas production, no smog, no acid rain
- No possibility of runaway reaction or meltdown
- No proliferation threat (not a credible bomb factory)
- Only short-lived radioactive wastes (due to neutron bombardment of vessel material)



Disadvantages of fusion energy

- Large power plant
 - Power a city, but not a car (although could produce hydrogen fuel)
- Expensive
 - Costly development path: plant cost is comparable to coalburning plant with same output
- Complicated
 - Plasma dynamics
 - Maintenance
- There is no fusion power plant (yet)

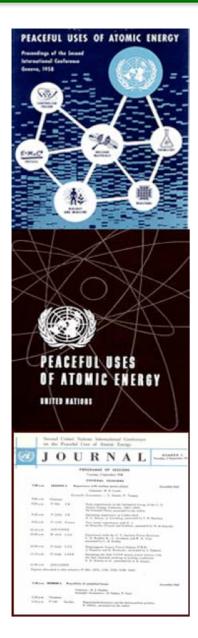


Producing a self-sustaining fusion-heated plasma is a grand challenge

1928	Fusion reactions explain energy radiated by stars [Atkinson & Houtermans]	
1932	Fusion reactions discovered in laboratory [Oliphant]	
1935	Fusion reactors understood as Coulomb barrier tunneling [Gamow]	
1939	Theory of fusion power cycle for stars [Bethe–Nobel Prize 1967]	
1950	US approval to develop hydrogen bomb "Super" [Teller]	
1951-52	Invention of the tokamak [Tamm and Sakharov]	
1950's	US Project Sherwood (classified) on controlled thermonuclear fusion	
1958	2 nd UN Atoms for Peace Conference (Geneva): declassification of magnetic fusion research	
1968	Russian tokamak results with high temperature presented at IAEA Fusion Energy Conference	
Since then:	Worldwide explosion in tokamak research, culminating in experiments on TFTR (US), JET (EU), JT-60U (Japan), etc.	



50 years of fusion research



- 2nd UN Conference on Peaceful Uses of Atomic Energy (Geneva, 1958)
 - 5000 scientists from 67 countries, plus 900 correspondents and 3651 industrial observers
 - 2137 papers, of which 109 covered fusion topics (from 11 countries)
 - This conference marked the beginning of the modern worldwide fusion program, with its emphasis on international unclassified cooperation and its awareness of the potential benefit of fusion energy for all humanity



22nd IAEA Fusion Energy Conference (2008)













Across a half century





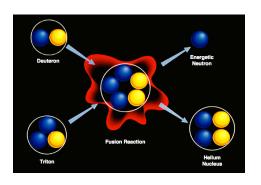
1958 2008

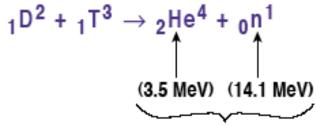
Source: IAEA commemorative booklet





- The "easiest" fusion reaction uses hydrogen isotopes: deuterium (D) and tritium (T)
 - D is plentiful in sea water
 - T can be generated from lithium
 - He is harmless (even useful)

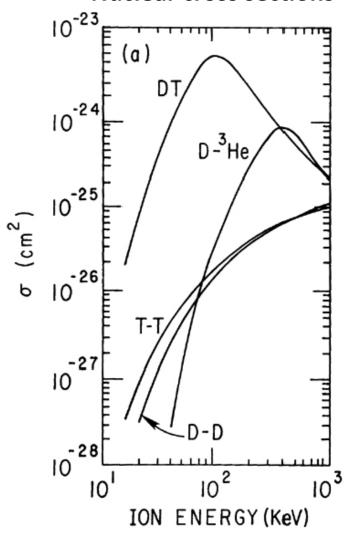




Energy/Fusion: $\varepsilon_f = 17.6 \text{ MeV}$









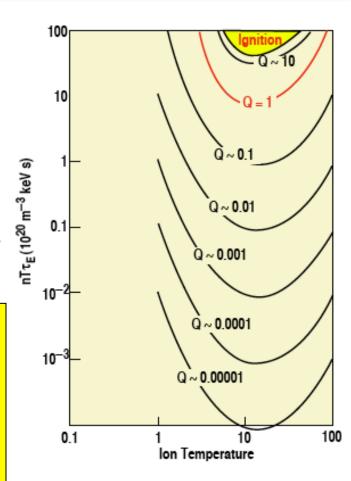
Fusion "gain" Q

$$\frac{dW}{dt} \rightarrow 0 \implies P_{\alpha} + P_{heat} = \frac{W}{\tau_E}$$

Define fusion energy gain,
$$Q = \frac{P_{\text{fusion}}}{P_{\text{heat}}} = \frac{5 P_{\alpha}}{P_{\text{heat}}}$$

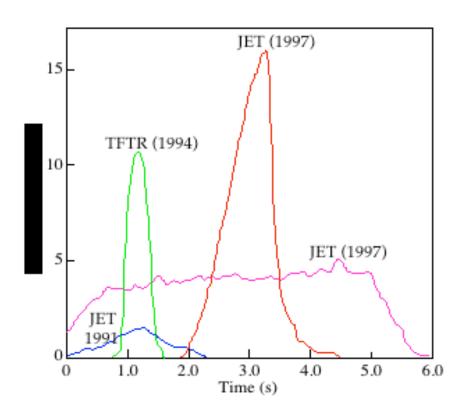
Define
$$\alpha$$
-heating fraction, $f_{\alpha} \equiv \frac{P_{\alpha}}{P_{\alpha} + P_{heat}} = \frac{Q}{Q+5}$

Breakeven	Q = 1	f _α = 17%
Burning plasma regime	Q = 5 Q = 10 (ITER) Q = 20 Q = ∞	$f_{\alpha} = 50\%$ $f_{\alpha} = 60\%$ $f_{\alpha} = 80\%$ $f_{\alpha} = 100\%$





Initial D-T experiments



Source: J. Jacquinot

Joint European Torus (JET)

- "Preliminary Tritium Experiment" (1991):
 P_{DT} > 1 MW
- Subsequently: Q=0.9 (transient breakeven), Q=0.2 (long pulse)
- 16 MW fusion power

Tokamak Fusion Test Reactor (TFTR)

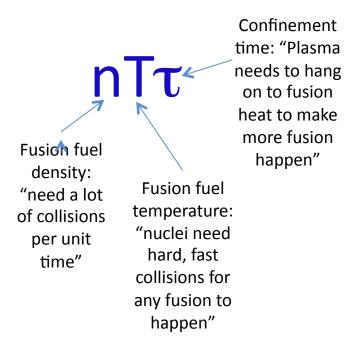
- Dec 1993 to Apr 1997: 1000 discharges with 50/50 D-T fuel
- $P_{DT} = 10.7 MW, Q=0.2 (long pulse)$
- Results:
 - Favorable isotope scaling
 - Self-heating by alpha particles
 - Alpha-driven instability
 - Tritium and helium "ash" transport
 - Tritium retention in walls and dust
 - Safe tritium handling (1M curies)

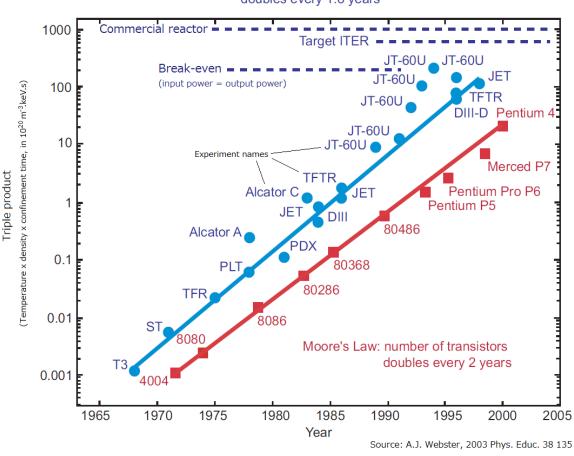


Significant progress

doubles every 1.8 years

fusion triple product





Fusion: figure-of-merit (the 'triple product')

Fusion works in the lab: a 10,000-fold increase in 30 years, another factor of 6 for a power plant



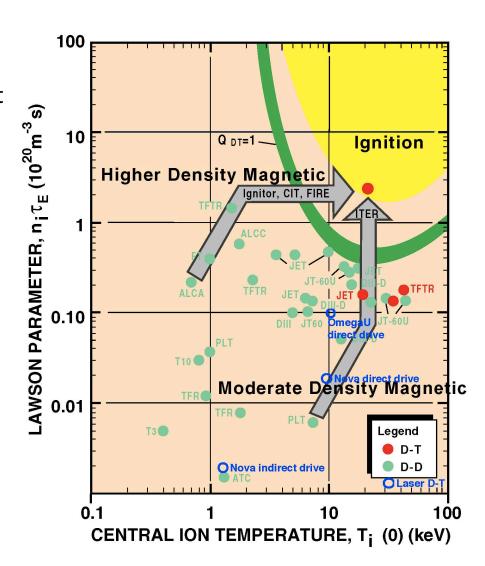
Status of magnetic fusion

Lawson Diagram:

- Achieved T_i required for fusion, but need ~10 x n τ_F
- Achieved n $\tau_E \approx \frac{1}{2}$ required for fusion, but need ~10 x T_i

No experiment has yet entered the burning plasma regime

- Such an experiment is the next logical step forward on the path to fusion energy
- The world fusion program is technically and scientifically ready to proceed now with a burning plasma experiment





US Fusion Energy Sciences program supports both fusion and plasma science

Objectives Mission energy

The mission of the US Fusion Energy Sciences (FES) program is to expand the fundamental understanding of matter at very high temperatures and densities and to build the scientific foundations needed to develop a fusion energy source. This is accomplished by the study of the plasma state and its interactions with its surroundings.

- Advance the fundamental science of magnetically confined plasmas for fusion
- Pursue scientific opportunities and grand challenges in high energy density plasma science
- Support the development of the scientific understanding required to design and deploy fusion materials
- Increase the fundamental understanding of plasma science beyond burning plasmas



Diversity of institutions and science





U.S. Fusion Energy Sciences: snapshot

High Energy Density Plasmas

Inertial Fusion Energy Science Materials in Extreme Conditions Instrument (MECI) @ SLAC-LCLS



Joint Program with National Nuclear Security Administration







General Plasma Science



NSF/DOE Partnership in Basic Plasma Science

Max Planck Princeton Research
Center for Plasma Physics



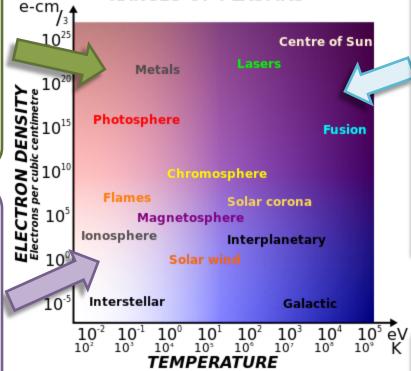
Low Temperature Plasma



Basic Plasma Science Facility



RANGES OF PLASMAS



Mission of the Fusion Energy Sciences program

To expand the fundamental understanding of matter at very high temperatures and densities and build the scientific foundations needed to develop a fusion energy source. This is accomplished by the study of the plasma state and its interactions with its surroundings.

Magnetic Confinement Fusion

Facilities



DIII-D





C-Mod

MST



Experimental Plasma Research

Diagnostics

Theory & Simulation, SciDAC



International collaborations

Enabling R&D

Fusion Materials Science
Enabling Technology
Advanced Design





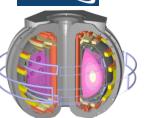


U.S. Fusion Energy Sciences: facilities

Magnetic Confinement Fusion facilities





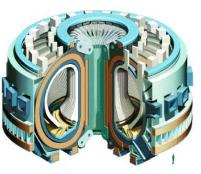






ITER Project international facility





General Plasma Science facilities









Experimental Plasma Research facilities







High Energy Density facilities (with NNSA and BES)















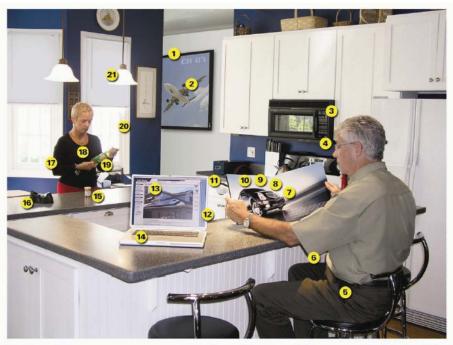
Warm Dense Matter







Low temperature plasma science



- 10-Plasma muffler
- 11—Plasma ozone water purification
- 12-Plasma-deposited LCD screen
- 13-Plasma-deposited silicon for solar cells
- 14—Plasma-processed microelectronics
- 15-Plasma-sterilization in pharmaceutical production
- 16-Plasma-treated polymers
- 17-Plasma-treated textiles
- 18-Plasma-treated heart stent
- 19—Plasma-deposited diffusion barriers for containers
- 20—Plasma-sputtered window glazing
- 21-Compact fluorescent plasma lamp

- 01—Plasma TV
- 02—Plasma-coated jet turbine blades
- 03—Plasma-manufactured LEDs in panel
- 04—Diamondlike plasma CVD eyeglass coating
- 05-Plasma ion-implanted artificial hip 09-Plasma-aided combustion
- 06-Plasma laser-cut cloth
- 07-Plasma HID headlamps
- 08-Plasma-produced H, in fuel cell

University of Michigan

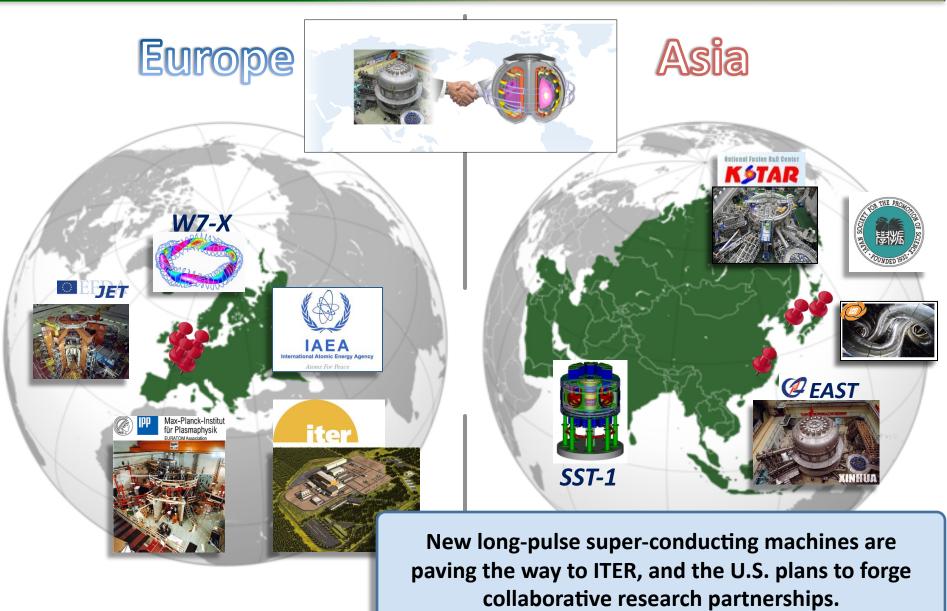
The new Center for Predictive Control of Plasma Kinetics: Multi-phase and Bounded Systems is funded by a fiveyear grant from the U.S. DOE. The Center is enabling fundamental research on low-temperature plasmas ionized gases with vast potential for practical technological advancements. In particular, the Center will investigate techniques to customize the distributions of charged particles (electrons and ions) in these plasmas. A vast array of modern technologies, including renewable energy sources, lighting, microelectronics, and medicine, would not exist in the absence of low-temperature plasmas. The fundamental research that is being conducted at the Center could lead to more efficient solar cells, finerfeatured microchips and new medical tools that cut and heal tissues with plasma-activated chemistry.

Source: Prof. Mark Kushner. review talk, 2008 APS-DPP Annual Meeting

From the Plasma 2010 Decadal Study of the National Academies: "To fully realize the opportunities in plasma research, a unified approach is required. Therefore, the Department of Energy's Office of Science should reorient its research programs to incorporate magnetic and inertial fusion energy sciences, basic plasma science, non-mission-driven high-energy density plasma science, and low-temperature plasma science and engineering."



Global cooperation opportunities

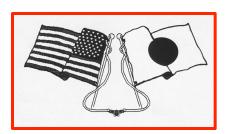




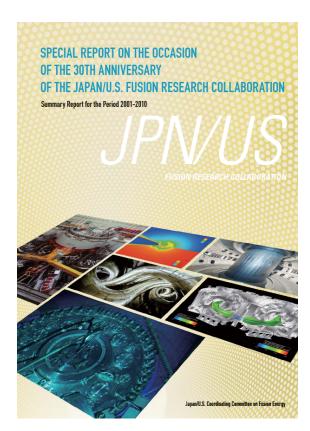
30-year anniversary of US-Japan fusion collaborations (1980-2010)



Participants at 13 Oct 2010 Meeting of the US-Japan Coordinating Committee on Fusion Energy (CCFE) at which the 30th anniversary of US-Japan Cooperation Activity was celebrated







30th anniversary report (234 pages, CCFE, 2011)



Opportunities for junior scientists in fusion energy and plasma science

Universities



Undergraduate Fellowships

Summer Undergrad Lab Instruction (SULI)

Nat'l Undergrad Fellowship

Graduate Fellowships

SC graduate fellowship

Postdoctoral Fellowships

ORISE Fusion PD Fellowship

Early Career Awards

PPPL Off Site University Research Program

Visiting Faculty Program

National Labs



Undergraduate Fellowships

SULI

NUF *

Graduate Fellowships

SC graduate fellowship

Postdoctoral Fellowships *

ORISE Fusion PD Fellowship

Early Career Awards

Industry R&D



Government



Graduate Fellowships

Mass Media Fellowship Program

Postdoctoral Fellowships

AAAS Science & Tech Policy
APS Congressional Science

IPAs & Detailees

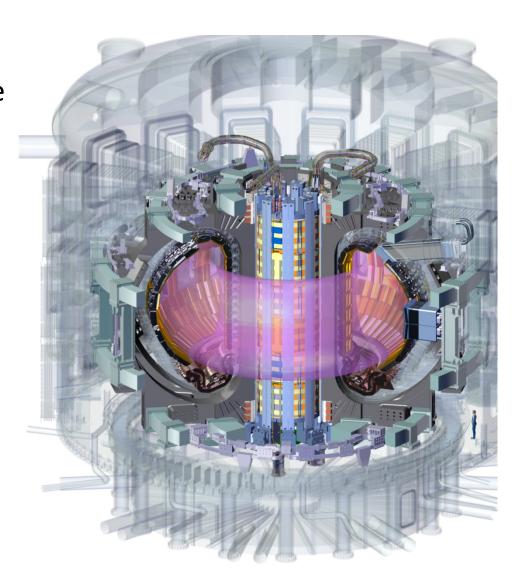


ITER is the next frontier

The ITER Project represents the next frontier in energy generation and will deliver an international scientific laboratory that demonstrates *hydrogen fusion* as a practical source of electricity in the 21st century

International Thermonuclear Experimental Reactor

ITER = "the way" (Latin)

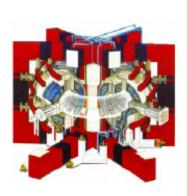




ITER is ambitious



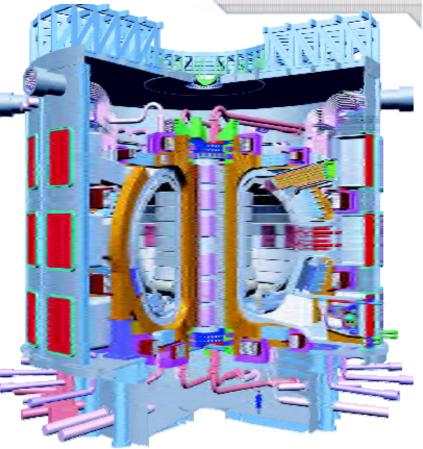
ITER is twice as large as the largest existing EU facilities



Tore Supra JET V_{plasma} 25 m^3 V_{plasma} P_{fusion} ~0 P_{fusion} t_{plasma} ~400 s t_{plasma} Source: ITER Organization

JET $V_{plasma} = 80 \text{ m}^3$ $P_{fusion} = ~16 \text{ MW 2s}$ $t_{plasma} = ~30 \text{ s}$

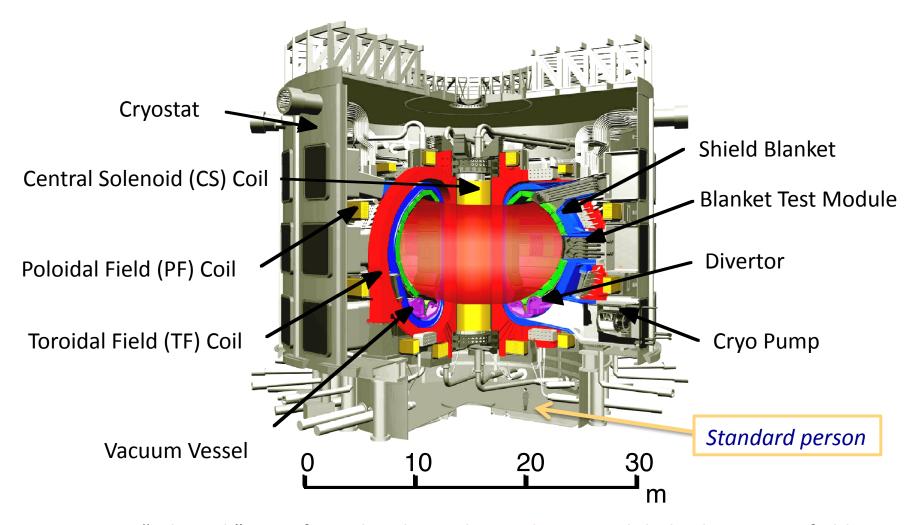
200 million °C (10 X core of Sun)



 $ITER \\ V_{plasma} & 830 \text{ m}^3 \\ P_{fusion} & \sim 500 \text{ MW } 500\text{s} \\ t_{plasma} & \sim 400 \text{ s}$



Cutaway view of ITER



ITER is a "tokamak" = confines doughnut-shape plasma with helical magnetic fields

Source: U.S. ITER Project Office 34



Deciding on the site for ITER

$4 \rightarrow 2 \rightarrow 1$



Japan - Rokkasho



Canada - Clarington



Spain - Vandellòs



France - Cadarache

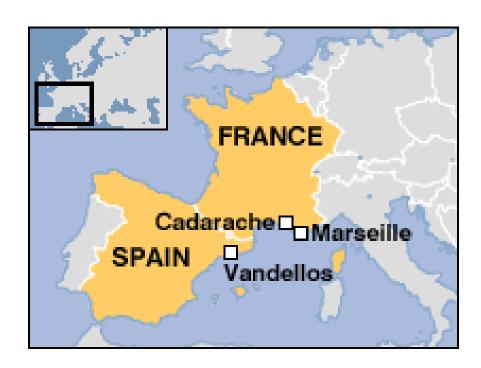
2LV8R





Being built in Cadarache, France (EU)

- Near Marseille (in Provence-Alpes-Cote d'Azur region)
- Estimated first plasma operation in ~2019, D-T operation by ~2027

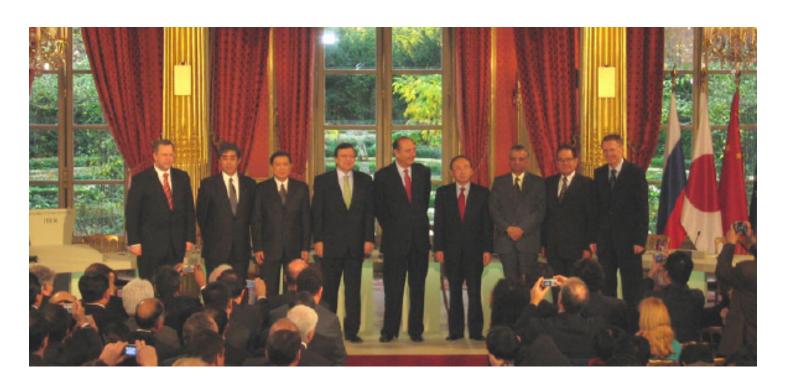




Source: ITER Organization



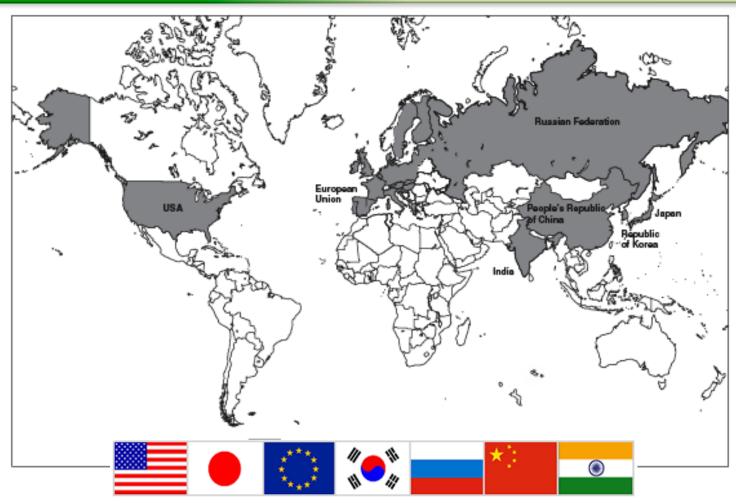
ITER: an international project



- ITER Joint Implementing Agreement signed 21 Nov 2006
 - Signing ceremony hosted by French President Chirac (Paris)
 - ITER Members = EU, Japan, Russia, USA, Korea, China, and India



US is one of seven ITER partners



- ITER Members = EU, Japan, Russia, US, Korea, China, India
 - 7 international partners represent 50% of world's population

Source: ITER Organization

ITER design goals



Physics:

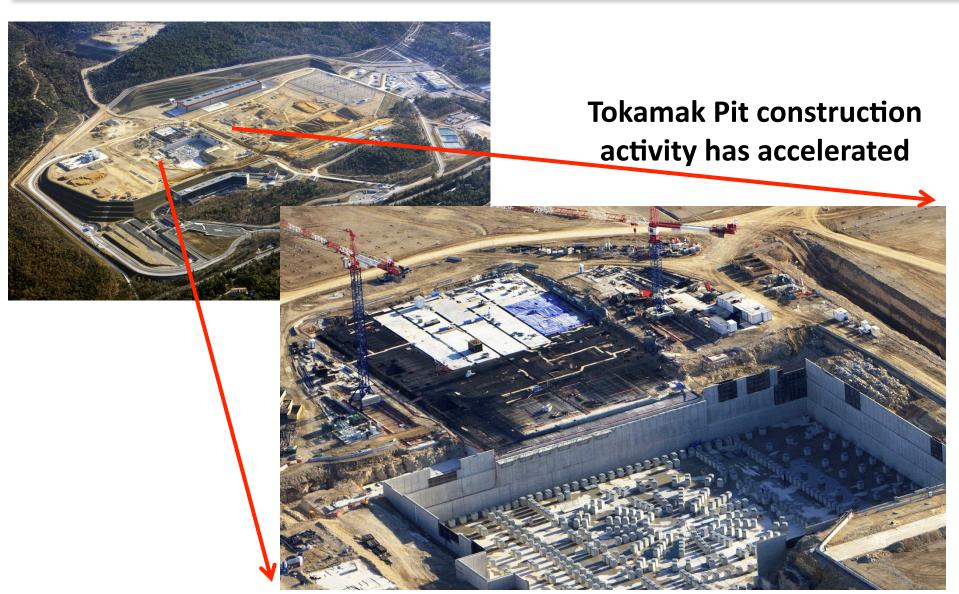
- Produce a plasma dominated by alpha particle heating
- Produce significant fusion power amplification (Q ≥ 10) in long-pulse operation
- Achieve steady-state operation of a tokamak (Q =5)
- Retain the possibility of exploring "controlled ignition" (Q ≥ 30)

Technology:

- Demonstrate integrated operation of technologies for a fusion power plant
- Test components required for a fusion power plant
- Test concepts for a tritium breeding module



ITER Project is moving forward rapidly



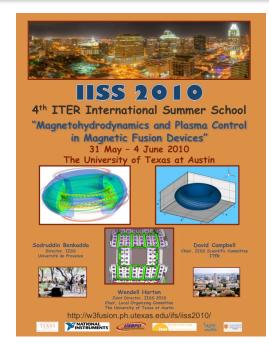
Source: ITER Organization

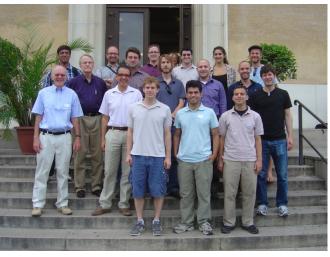


ITER International School

U.S. Burning Plasma Organization (USBPO) provides scholarships for US participants

- 4th ITER School (May 2010) was held in the US
 - "MHD and Plasma Control"
- 5th ITER School (June 2011) held in France
 - "Energetic Particles"
- 6th ITER School (Dec 2012) was held in India
 - "RF Heating and Current Drive"







Energy challenge for 21st century

- World energy use will likely double by 2045
- Continued reliance on fossil fuels will cause unacceptable climate changes
- Serious R&D programs are needed to find alternative sources of energy
 - Present research investment is small, compared to \$3 trillion world energy market



Solutions to the energy problem

Approaches:

- Decreased consumption
- Improved efficiency for fossil fuel use
- Renewables: solar, wind, geothermal, ...
- Fission ("split" the atom)
- Fusion (combine light atoms)
- A hybrid energy portfolio that combines all of these approaches will probably be necessary





The Case for Fusion, by P. K. Kaw and I. Bandyopadhyay

- Chapter 1 in the book <u>Fusion Physics</u>, edited by M. Kikuchi,
 K. Lackner, and M.Q. Tran (IAEA, Vienna, 2012)
- "In conclusion, then, in the short term of the next 30-40 years, the world energy scenario is likely to be still dominated by gradually depleting fossil fuels, with nuclear fission and renewables taking a gradually increasing share. During this time fusion energy will establish itself through experiments like ITER and demonstration power plants like DEMO. In the long term, towards the end of this century, however, fusion power is likely to become commercial and play an increasingly dominant role in the world energy scenario."



Vision for the future



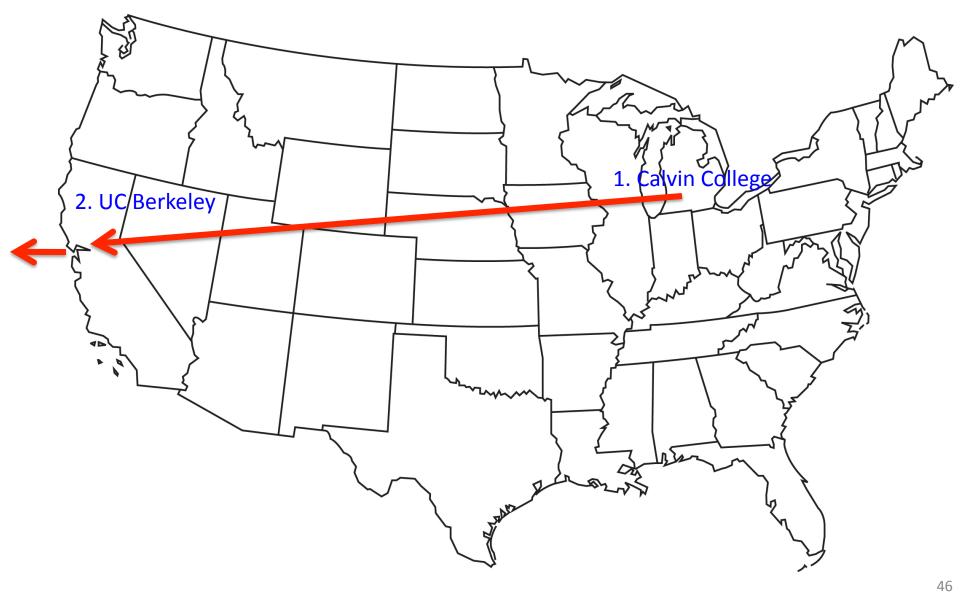
Ultimate goal:

Abundant, clean fusion energy to power the world for the benefit of society

"Fusion City"

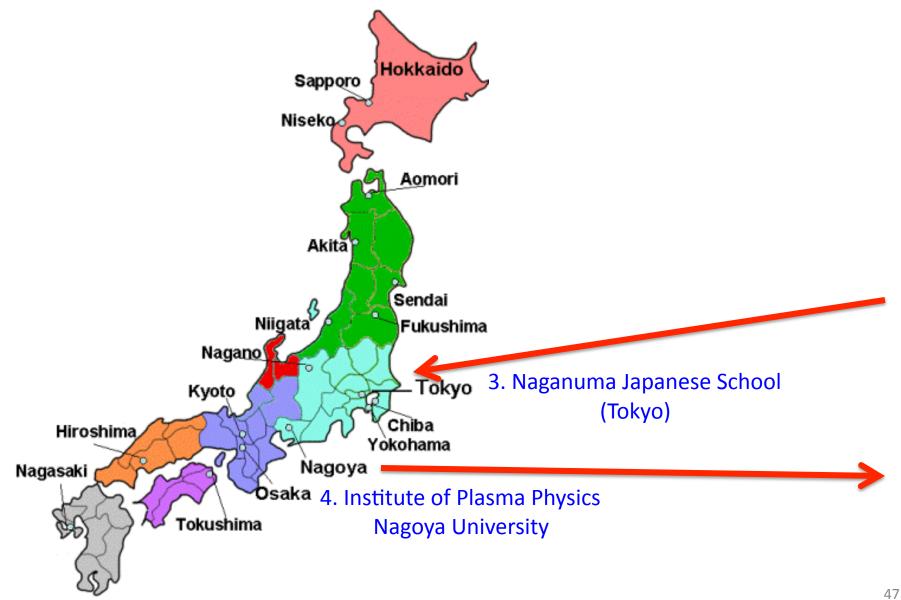


Scientific trajectory (1)



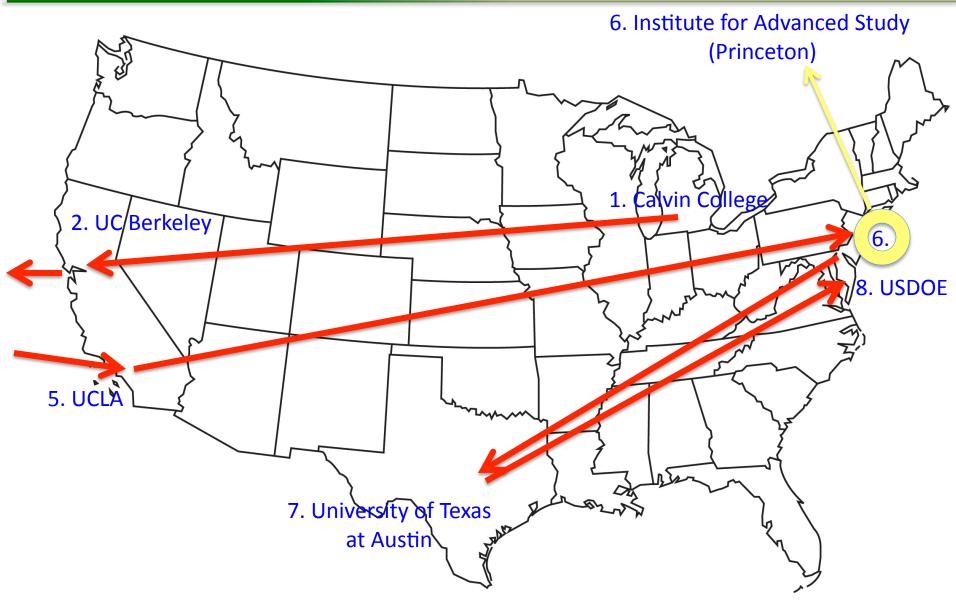


Scientific trajectory (2)





Scientific trajectory (3)





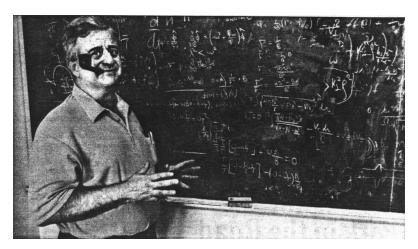
"Pope" of plasma physics

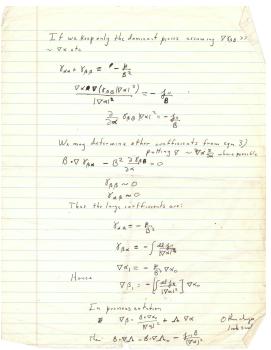
Prof. Marshall N. Rosenbluth

- Career in high-energy physics, national security, and plasma physics
- Member, National Academy of Sciences
- Before Texas: Professor at Institute for Advanced Study (Princeton)
- At University of Texas: Director,
 Institute for Fusion Studies
- After Texas: Chief Scientist, ITER Organization (EDA phase)

"From Yearning to Burning" (2000)

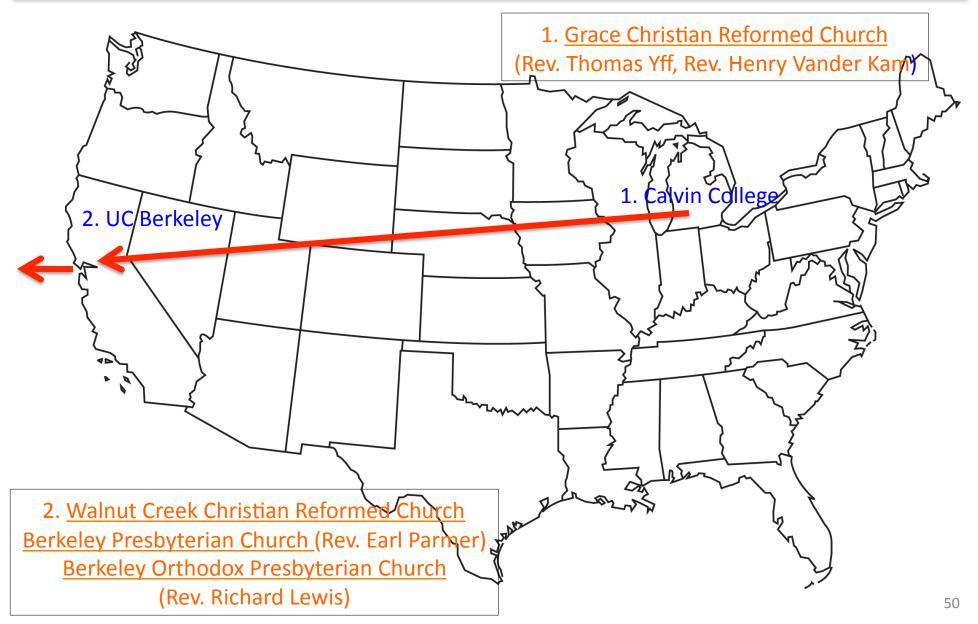
 "The 'yearn to burn' is well motivated. Most of us came into the fusion program with the dream of fusion energy. The dream persists."





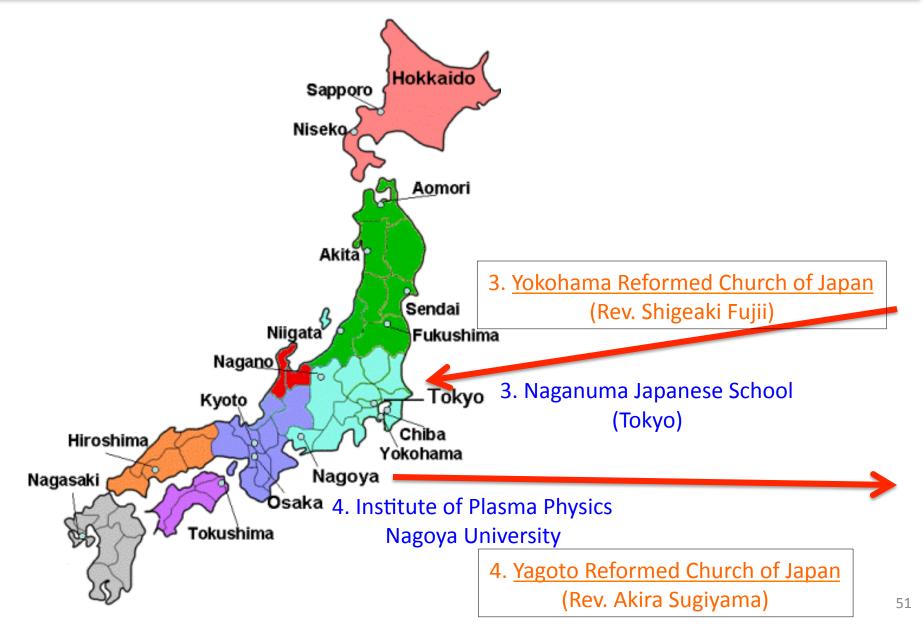


Faith & church trajectory (1)



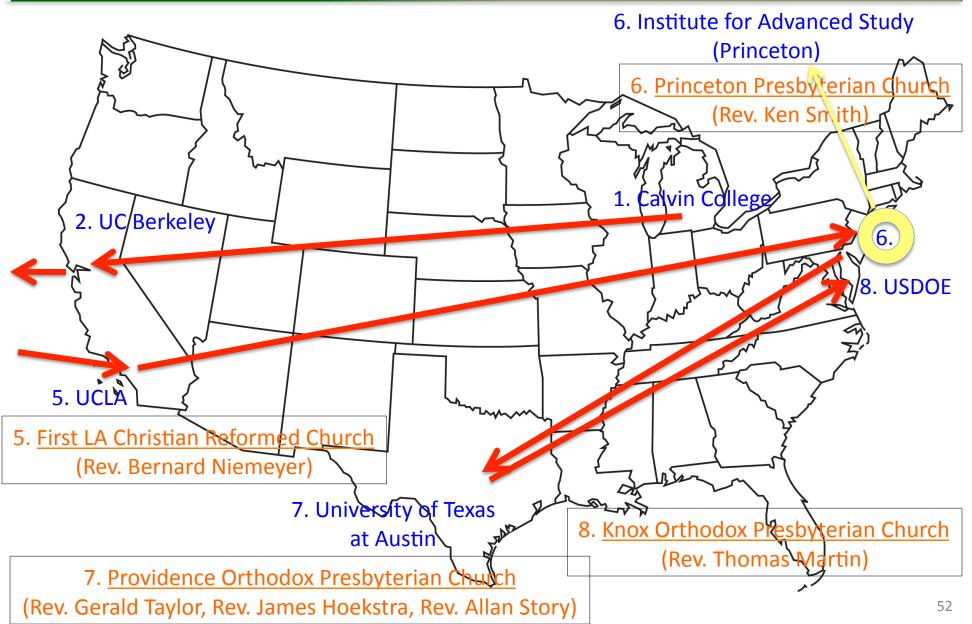


Faith and church trajectory (2)





Faith & church trajectory (3)





Exemplary Christian faith

Rev. Shigeaki Fujii (pastor, teacher), wife Mrs. Masa Fujii, & Miss Jesse Riker









1941 1953 1992







"I will dwell in the house of Jehovah forever." $_{53}$

1993

1995

7

Federal service

Believers can contribute in this arena

 Examples in Scripture: Joseph, Daniel, King David's officials (II Sam 8:15-17)

Career path:

— research → management → policy (→ philosophy?)

Differences between academe and government:

- On oath
- Security aspects
- Work to deadlines (unscheduled), "manage the chaos"
- Many meetings (often videoconferences)
- Fast/accurate/honest/reliable/legal
- No surprises
- Plan far ahead
- Team work & delegation



Motivated by service

"For me, the most significant benefit in working for the Federal government is the opportunity to serve my country in a capacity that utilizes my strengths and skills..."

Dr. Sean Finnegan

From Office of Science web site

What do you think is the "coolest" thing about your job?

The "coolest" thing about my job, hands down, is getting to know the genuinely brilliant researchers and students whose work is critical not only to addressing the scientific questions underpinning fusion as a viable long-term energy solution and to strengthening our national security, but is also vital in continuing to expand the boundaries of human knowledge.

What would you say to a potential candidate that would convince her/him to join your organization or the Federal government?

If you are not just looking for a job, but a career, that will challenge you in ways you likely never imagined, then you can't do better than this. I can promise you that no two days will be the same and that you will have the opportunity to have a real and significant impact on your country and perhaps the world.



Some guiding Scripture verses

- "Abstain from all appearance of evil." (I Thess 5:22)
 - Conflict of interest
- "Whoever meddles in a quarrel not his own is like one who takes a passing dog by the ears." (Proverbs 26:17)
- "Everyone should be quick to listen, slow to speak, and slow to become angry." (James 1:19)
- "When words are many, transgression is not lacking, but whoever restrains his lips is prudent." (Proverbs 10:19)



Striving to be pithy





Source: Dr. Sean Finnegan



More guiding Scripture verses

- "For the man will not rest until he has concluded the matter this day." (Ruth 3:18)
- "Where there is no guidance, a people falls, but in an abundance of counselors there is safety." (Proverbs 11:14)
 - Peer review process, federal advisory committees
- "Thus Joseph, who was also called by the apostles Barnabas (which means son of encouragement), a Levite, a native of Cyprus, sold a field that belonged to him and brought the money and laid it at the apostles' feet." (Acts 4:36-37)





• "I have been crucified with Christ. It is no longer I who live, but Christ who lives in me. And the life I now live in the flesh I live by faith in the Son of God, who loved me and gave himself for me." (Galatians 2:20)

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