“50” Years of Fusion Research

Dale Meade
Fusion Innovation Research and Energy®
Princeton, NJ

Independent Activities Period (IAP)
January 19, 2011
MIT PSFC Cambridge, MA 02139
Fusion Fire Powers the Sun

“We need to see if we can make fusion work.”

John Holdren @MIT, April, 2009
Path of Progress for Fusion Energy Science

... developing safe uses of atomic energy
Toroidal Magnetic Confinement (1940s-early 50s)

• **1940s** - first ideas on using a magnetic field to confine a hot plasma for fusion.

• **1947**  Sir G.P. Thomson and P. C. Thonemann began classified investigations of toroidal “pinch” RF discharge, eventually lead to ZETA, a large pinch at Harwell, England 1956.

• **1949**  Richter in Argentina issues Press Release proclaiming fusion, turns out to be bogus, but news piques Spitzer’s interest.

• **1950**  Spitzer conceives stellarator while on a ski lift, and makes proposal to AEC ($50k)-initiates Project Matterhorn at Princeton.

• **1950s**  Classified US Program on Controlled Thermonuclear Fusion (Project Sherwood) carried out until 1958 when magnetic fusion research was declassified. US and others unveil results at 2nd UN Atoms for Peace Conference in Geneva 1958.
Fusion Leading to 1958 Geneva Meeting

• A period of rapid progress in science and technology
  – N-weapons, N-submarine, Fission energy, Sputnik, transistor, ....

• Controlled Thermonuclear Fusion had great potential
  – Much optimism in the early 1950s with expectation for a quick solution
  – Political support and pressure for quick results (but budgets were low, $56M for 1951-1958)
  – Many very “innovative” approaches were put forward.
  – Early fusion reactor concepts - Tamm/Sakharov, Spitzer (Model D) very large.

• Reality began to set in by the mid 1950s
  – Collective effects - MHD instability (1954), Bohm diffusion was ubiquitous
  – Meager plasma physics understanding led to trial and error approaches
  – A multitude of experiments were tried and ended up far from fusion conditions
  – Magnetic Fusion research in the U.S. declassified in 1958
Plasma Requirements for a Burning Plasma (Lawson Criteria)

J. D. Lawson, Secret Internal Memo 1955,

**Power Balance**

\[ P_{\text{aux-heat}} + n^2 \langle \sigma v \rangle U_\alpha V_p / 4 - C_B T^{1/2} n_e^2 V_p = 3nkTV_p / \tau_E + d(3nkTV_p) / dt \]

where: \( n_D = n_T = n_e / 2 = n/2 \), \( n^2 \langle \sigma v \rangle U_\alpha V_p / 4 = P_\alpha \) is the alpha heating power,
\( C_B T^{1/2} n_e^2 V_p \) is the radiation loss, \( W_p = 3nkTV_p \) and
\( \tau_E = W_p / (P_{\text{aux-heat}} - dW_p / dt) \) is the energy confinement time.

**In Steady-state:**

\[
\begin{align*}
n\tau_E & = \frac{3kT}{\langle \sigma v \rangle U_\alpha (Q+5)/4Q - C_B T^{1/2}} \\
& \quad \text{where } Q = P_{\text{fusion}} / P_{\text{aux-heat}} \\
Q = 1 & \text{ is Plasma Breakeven, } \quad Q = \infty & \text{ is Plasma Ignition}
\end{align*}
\]
The Lawson Diagram in 1958

- **Lawson Parameter,** $n_i T_i (10^{20} \text{m}^{-3} \text{s})$
- **Central Ion Temperature,** $T_i (0) \text{(keV)}$

- **3 x 10^4**
- **3 x 10^3**

- $Q_{DT}=1$ ignition line
The stellarator as first proposed by Spitzer May 1951 was a thermonuclear power generator based on a linear cylinder with uniform magnetic field. A toroidal stellarator based on a Figure 8 was described later, helical windings were introduced ~ 1960.

- $T \sim 10$ eV, $n \sim 10^{13}$ cm$^{-3}$, $\tau_E \sim$ few $\mu$s, Bohm- scaling, a few non-thermal neutrons
Fusion Plasma Physics, a New Scientific Discipline, was born in the 1960s

• **Theory of Fusion Plasmas**
  – Energy Principle developed in mid-50s became a powerful tool for assessing macro-stability of various configurations
  – Resistive macro-instabilities
  – Linear stability analyses for idealized geometries revealed a plethora of microinstabilities with the potential to cause anomalous diffusion Trieste School
  – Neoclassical diffusion developed by Sagdeev and Galeev (mentioned by Sakharov in the early 50s).
  – Wave propagation became basis for RF heating

• **Experimental Progress (some examples)**
  – Most confinement results were dominated by instabilities and ~ Bohm diffusion
  – Stabilization of interchange instability by Min|B| in mirror - Ioffe
  – Stabilization of interchange in a torus by Min<B> in multipoles - Kerst/Ohkawa
  – Quiescent period in Zeta due to strong magnetic shear in self-organized state
  – Confinement gradually increased from 1 τ_B to 5-10 τ_B for low temp plasmas
  – Landau Damping demonstrated
The Mid 1960s - First Stabilization of Interchange in Mirror

• The first mirror in the late ’50s were plagued with instabilities. Mirrors were afflicted by “interchange instabilities.”

• 1962 New ideas emerge to stabilize the plasma. Linear multipole coils added to simple mirror create a min-B well to stabilize the interchange.

Ioffe - IAEA Proceedings Plasma Physics and Contolled Fusion 1, 39, 1965
Stabilization of MHD Interchange by Geometry (minimum $|B|$) in a Mirror Machine

Increasing $B_{\text{multipole}}$

Fusion Plasma Physics, a New Scientific Discipline, was born in the 1960s

- Theory of Fusion Plasmas
  - Energy Principle developed in mid-50s became a powerful tool for assessing macro-stability of various configurations
  - Resistive macro-instabilities
  - Linear stability analyses for idealized geometries revealed a plethora of microinstabilities with the potential to cause anomalous diffusion Trieste School
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  - Stabilization of interchange in a torus by $\text{Min}<B>$ in multipoles - Kerst/Ohkawa
  - Quiescent period in Zeta due to strong magnetic shear in self-organized state
  - Landau Damping demonstrated in a linear experiment
  - Confinement gradually increased from $1\ \tau_B$ to $5-10\ \tau_B$ for low temp plasmas
The Mid 1960s - Bohm Barrier Broken in a Torus

- 1962 - Toroidal Multipoles built to test \( \int \frac{dl}{B} \) stabilization. \( \int \frac{dl}{B} \) is the volume of a flux tube. \( \nabla \rho \cdot \nabla \int \frac{dl}{B} > 0 \) for stability.

DMM Phys Rev Lett 17, 677, 1966
R = 1 m, a = 0.12m, B ≤ 3.5T, Ip < 80 kA, Ohmic heating only
1968-69 T-3 Breaks Bohm, Tokamaks Proliferate

- Hints of a major advance at IAEA Novosibirsk 1968, but skeptics abound

- Thomson Scattering (Peacock/Robinson) Dubna 1969 confirms $T_e \approx 1$ keV

- Energy confinement $\approx 30 \tau_B$ - Bohm barrier broken for a hot plasma

- Skeptics converted to advocates overnight, the phone lines from Dubna to Princeton were busy with instructions to modify Model C.
Model C Stellarator Converted to Tokamak in 6 months

T-3 results are quickly reproduced and extended. $T_e \sim 1 \text{ keV}$

Symmetric Tokamak (ST)
1970

Model C Stellarator
1969
$T_e \sim 40 \text{ eV}$
1968-69 T-3 Breaks Bohm, Tokamaks Proliferate

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- Thomson Scattering (Peacock/Robinson) Dubna 1969 confirms $T_e \approx 1$ keV
- Energy confinement $\approx 30 \tau_B$ - Bohm barrier broken for a hot plasma
- Skeptics converted to advocates overnight, Model C Stellarator converted to Symmetric Tokamak (ST) in 6 months, T-3 results are quickly reproduced.

- During the 1970’s ~ many medium size ($I_p < 1$ MA) tokamaks (TFR, JFT-2a, Alcator A, Alcator C, ORMAK, ATC, PLT, DITE, DIII, PDX, ASDEX, ...) were built with the objectives of:
  - Confinement scaling with size, $I_p$, $n$, $T, \ldots$
  - Auxiliary heating (compression, ICRF, NBI, ECRH, LH)
  - Current Drive (LH, NBI, ...)
  - Impurity control (limiters, divertors)
• Logic III became the basis for the MFE Act of 1980.
Fusion was Prepared for a Major Next step when Opportunity Knocked (1973 Oil Embargo)

- Amid calls for increased energy R&D, Fusion budgets rise sharply
  - US Fusion budget increased a factor of 15 in 10 yrs.
  - 4 Large Tokamaks approved for construction less than a decade after T-3
    - TFTR
    - JET shaped plasma - const began 1977
    - JT-60 poloidal divertor - const began 1978
    - T-15 Superconducting TF (NbSn) const began 1979

These were very large steps, taken before all the R&D was completed.

Plasma Current 0.3 MA $\rightarrow$ 3MA to 7MA
Plasma Volume $1 m^3 \rightarrow 35 m^3$ to $100 m^3$

Auxiliary Heating 0.1 MW $\rightarrow$ 20 MW to 40 MW

J. Willis, MacFusion
Optimism about Confinement Increased in the late 1970s

- Trapped Ion instabilities were predicted in the early 1970s to be a threat to the achievement high $T_i$ in tokamak geometries.

- In ~1979 Alcator A with only ohmic heating achieved $n\tau_E \approx 1.5 \times 10^{19} \text{ m}^{-3} \text{s}$, consistent with optimistic scaling $\tau_E \sim na^2$.

- In 1978, $T_i \sim 5.8$ keV was achieved in a collisionless plasma reducing concerns about Trapped Ion instabilities. $T_i$ was increased to 7 keV in 1980.
Auxiliary heating allowed controlled experiments to reveal the scaling of the global confinement time.

Confinement degradation observed as heating power was increased - Low mode scaling would threaten objectives of the large tokamaks, and tokamak based reactors.
H-Mode Discovered on ASDEX- 1982

- Facilitated new insights and understanding of transport, and
- Provided the baseline operating mode for ITER

$P_{\text{NBI}} = 2.6 \text{ MW H in D}$
$B_o = 2.2 \text{ T}$
$I_p = 320 \text{ kA}$
Configuration: $\text{SN}^+$

Two branches:
- Type „a“: L-mode
- Type „b“: H-mode

F. Wagner, IPP
Tokamak Optimization

• By the early 80s

  • It was clear tokamak performance would need to be improved, if the tokamak were to lead to an attractive fusion power source. The US initiates an Advanced Tokamak Program (Toroidal Steering Committee => Ed Kintner 1979)

  • The benefits of cross-section shaping for increased confinement and beta were demonstrated and understood in Doublet IIA and Doublet III.

  • The $\beta$ limit formulation by Troyon and Sykes provided a design guide for $\beta$.

  • Empirical scaling formulations (e.g., Goldston scaling) provided guidance for $\tau_E$.

  • An understanding of divertors emerged from JFT-2a, PDX, ASDEX, DIII, DITE.

• A second generation of flexible optimized tokamaks: DIII-D, AUG, JT-60U, PBX, Alcator C-Mod were built in the late 1980s to extend and develop the scientific basis for advanced tokamaks.
Stage II - Approach Reactor Plasma Conditions

TFTR 1982-1997

JET 1983 - 2016?

JT-60U 1984-2008

T-15 1988 - 2005?
Large Tokamaks Extend Plasma Parameters

- After about 6 years of construction TFTR, JET and JT-60 began operation 1982-84.

- By the mid 80s, after 4 years of operation the plasma parameter range had been significantly extended:
  - $T_i \approx 20$ keV and $n_e(0)\tau_E \sim 1.5 \times 10^{19}$ m$^{-3}$ s with neutral beam injection
  - $n_e(0)\tau_E \sim 1.5 \times 10^{20}$ m$^{-3}$ s and $T_i \sim 1.3$ keV with pellet injection
  - H-Mode extended to large tokamaks, new improved performance regimes discovered.
  - Bootstrap current and current drive extended to MA levels
  - Divertor extended to large scale

- Complex Technology demonstrated at large scale

- Enabling Technology - Neutral beams, pellet injection, PFCs
Fusion Temperatures Attained, Fusion Confinement One Step Away

\[ n_i(0)\tau_E (10^{20} \text{ m}^{-3} \text{ s}) \]

Plasma Temperature (keV)

\[ n_i(0)\tau_E T_i \]

increased by \( \sim 10^7 \) since 1958

JAEA
Significant Fusion Power (>10MW) Produced 1990s

- **1991 JET 90/10-DT, 2 MJ/pulse, Q ~ 0.15, 2 pulses**

- **1993-97 TFTR 50/50-DT, 7.5MJ/pulse, 11 MW, Q ~ 0.3, 1000 D-T pulses,**
  - Alpha heating observed, Alpha driven TAEs - alpha diagnostics
  - ICRF heating scenarios for D-T
  - 1 MCi (100 g) of T throughput, tritium retention
  - 1 GJ of fusion energy, 3 years of safe operation with DT, and then decommissioned.

- **Advanced Tokamak Mode Employed for High Performance**
  - Improved ion confinement TFTR, DIII-D, $Q_{\text{DTequiv}} \sim 0.3$ in DIII-D 1995
  - $n\tau_E T$ record => $Q_{\text{DTequiv}}$ in JT-60U DD using AT mode 1996
  - Bootstrap and current drive extended

- **1997 JET 50/50-DT 22MJ/pulse, 16 MW, Q ~ 0.65, ~100 D-T pulses**
  - Alpha heating extended, ICRF DT Scenarios extended,
  - DT pulse length extended
  - Near ITER scale D-T processing plant
  - Remote handling
The Next Step - Burning Plasmas

• 1977 - Ignitor High field Cu coil proposed by B. Coppi to demonstrate ignition in MFE.

• 1979? - Riggatron extension of Ignitor idea to power production.

• 1980 - Fusion Engineering Device (FED), SC or Cu coils, 200 MW, 200s as part of MFE Act to be competed after expenditure of $1.6B

• 1980s - Several high field Cu designs put forward by MIT, eg, AFTR

• 1984 - Tokamak Fusion Core experiment (TFCX), SC coils, 200 MW, estimated cost $1.7B - cancelled too expensive

• 1986 - Compact Ignition Tokamak (CIT), LN Cu coils - 400 MW, 5 s, $0.7B

• 1989 - CIT was in FY89 budget with PACE funding for design, but was withdrawn by DOE (Hunter) when ignition could not be guaranteed.
Compact Ignition Tokamak (1986-1989)
Based on today’s understanding, CIT would have “ignited” with $Q = 35$ using a conservative $H_{98}(y,2) = 0.92$ !!!!
The Next Step - Burning Plasmas

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- 1990 - BPX a larger CIT with less ambitious goals and higher cost was put forward - cancelled in Sept 1991 (SEAB, Townes Panel) on to TPX

- 1992 - ITER - US joins ITER as one of four partners, has lead design center

- 1997 - US leaves ITER after completion of Engineering Design Activity

- 1998 - US initiates study of advanced CIT called FIRE
Snowmass 2002 - assessment of ITER, FIRE and Ignitor

- ITER/FIRE - similar H-Mode and AT physics capability
- ITER design complete with > 80 procurement packages ready to go to industry
- ITER First plasma planned for 2014, with DT in 2016?
- ITER total cost estimate = $5B, FIRE total cost estimate = $1.2B
  - US cost (10%) = $0.5B
  - US Cost (100%) = $1.2B

In 2003 US decides to join ITER
The Next Challenge -
Sustainment of Fusion Plasma Conditions

• **Steady-state operation is a highly desirable** characteristic for a magnetic fusion power plant. This requires:

  – Sustained magnetic configuration
    • The **stellarator** (helical) configuration is inherently steady-state, or
    • **Advanced tokamak** with high bootstrap current fraction and moderate external current drive is also a possible steady-state solution.

  – Effective removal of plasma exhaust and nuclear heat
    • Power density and distribution of removed power
    • Effect of self conditioned PFC on plasma behavior

• **Helical/Stellarator Resurgence**
  – Confinement, beta approaching tokamak
  – Opportunities for configuration optimization

• **Long Pulse Superconducting tokamaks** - T-7, T-15, Tore Supra, TRIAM, EAST, KSTAR, SST-1, JT-60SA
Realizing The Advanced Tokamak

- Plasma cross-section shaping to enhance plasma current, power production
  - 1968 Ohkawa (Plasma Current Multipole), 1973 T-9 Finger Ring,

- Bootstrap Current (self generated current)
  - Predicted 1971 - Bickerton – First observation 1983 in a multipole exp’t - Zarnstorff/Prager
  - Observed in 1986 in tokamak - TFTR - Zarnstorff

- Beta limit physics “understood” for tokamak
  - $\beta = \frac{\langle p \rangle}{B^2}$, 1983, Troyon, Sykes

- NTM Stabilized by ECRH ASDEX and DIII-D

- Resistive Wall Stabilization DIII-D ~2005

- Confinement enhancement by stabilizing ITG using Reversed Shear

- Reversed shear with a hollow current profile provides the above:
  - PEP modes on JET 1988
  - ERS modes on TFTR 1994
  - NCS modes on DIII-D 1994
  - RS modes on JT-60U 1995 - record $nT \tau$

- But all were transient

- Tihiro Ohkawa with toroidal multipole at GA 1966
Four New Superconducting Tokamaks will Address Steady-State Advanced Tokamak Issues in Non-Burning Plasmas

SST-1: \( R = 1.1 \text{m}, 0.22 \text{MA}, 2008 \)

EAST: \( R = 1.7 \text{m}, 2 \text{MA}, 2006 \)

KSTAR: \( R = 1.8 \text{m}, 2 \text{MA}, 2008 \)

JT-60SA: \( R = 3 \text{m}, 5.5 \text{ MA}, 2014 \)
Large Helical Device (LHD)

- External diameter: 13.5 m
- Plasma major radius: 3.9 m
- Plasma minor radius: 0.6 m
- Plasma volume: 30 m$^3$
- Magnetic field: 3 T
- Total weight: 1500 t

ECR 84 - 168 GHz

NBI (Ctr)

NBI (Perp)

Local Island Divertor (LID)

ICRF 25-100 MHz

- $T_e = 10$ keV, $T_i = 6.8$ keV
- $\langle \beta \rangle = 5\%$
- $n_e(0) = 1.1 \times 10^{21} m^{-3}$
- $n \tau_E T = 5 \times 10^{19} m^{-3} s$ keV

Long pulse: 0.6 MW for 1 hour
Wendelstein 7-X

First Plasma 2014

- Major radius: 5.5 m
- Minor radius: 0.53 m
- Plasma volume: 30 m³
- Induction on axis: 3T
- Stored energy: 600 MJ
- Machine mass: 725 t
- Pulse length: 30 min
- Aux Heating: 20-40 MW

W-7X is based on W-7AS, and is optimized to reduce bootstrap plasma currents, fast particle loss, neoclassical transport, with good flux surfaces, MHD stability and feasible coils.
An International Team is Forged to Develop a New Energy Source

- Agreed to “cooperation on fusion research” November 21, 1985 Geneva
- The IAEA provides the framework for International Collaboration
- By Dec 2005, EU, JA, RF, KO, CN, IN and US had signed ITER agreement
The Core of ITER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total fusion power</td>
<td>500 MW</td>
</tr>
<tr>
<td>Additional heating power</td>
<td>50 MW</td>
</tr>
<tr>
<td>Q - fusion power/ additional heating power</td>
<td>$\geq 10$</td>
</tr>
<tr>
<td>Average 14MeV neutron wall loading</td>
<td>$\geq 0.5$ MW/m²</td>
</tr>
<tr>
<td>Plasma inductive burn time</td>
<td>300-500 s *</td>
</tr>
<tr>
<td>Plasma major radius (R)</td>
<td>6.2 m</td>
</tr>
<tr>
<td>Plasma minor radius (a)</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Plasma current ($I_p$)</td>
<td>15 MA</td>
</tr>
<tr>
<td>Toroidal field at 6.2 m radius ($B_T$)</td>
<td>5.3 T</td>
</tr>
</tbody>
</table>

Machine mass: 23350 t (cryostat + VV + magnets)
- shielding, divertor and manifolds: 7945 t + 1060 port plugs
- magnet systems: 10150 t; cryostat: 820 t
ITER is Now Underway

ITER Site Under Construction

Reactor scale

First Plasma planned for 2018 ==> 2020

First DT operation planned for ~2022 ==> 2025
PATH OF PROGRESS FOR FUSION ENERGY SCIENCE

developing safe uses of atomic energy
Inertial Confinement Fusion (1940s-early 50s)

• **1942** - first ideas on using fusion reactions to boost A bomb yields.

• **1950** Teller given approval to develop Super (H-bomb), S. Ulam conceives two stage concept - second stage driven by radiation

• **1952** Greenhouse/Cylinder - 1951 test of radiation compression of 1 cm D-T pellet. First US H-bomb, Mike (liquid D$_2$) 1952, followed by a series of tests including Bravo (solid-LiD) 1954 at Bikini Atoll (MNR on observer ship exposed ~ 1R dose).


• References - Dark Sun by Richard Rhodes, Soviet Program Book
History of Soviet Fusion, V. D. Shafranov, Physics-Uspekhi 44(8) 835-865 (2001)
2. Ivy Mike, Nov 1, 1952; Cryo-Liquid D, Yield (8.5 Mt fission, 2.5 Mt fusion)
3. Castle Bravo, Mar 1 1954, Solid LiD, Yield 15 Mt (5 Mt expected)
MNR on observation ship received ~ 1 R
• Radiation compression of DT to produce fusion energy demonstrated in the early 50s in Greenhouse George Cylinder test (and others).

• Invention of the laser in early 60s offered the possibility of a programmable repetitive driver for micro targets. Research continued on intense particle beam drivers in USSR and US.

• Idealized calculations in late 60s suggested 1kJ needed to achieve breakeven using micro targets and direct drive.


• Laser driven experiments at LLNL and elsewhere from mid 70s to mid 80s (Nova), revealed importance of plasma instabilities and driver uniformity, raising required driver energy to MJ range.
Glass laser energy has increased $10^6$.

Fusion energy will need:
- increased efficiency
- increased repetition rate

- Janus: 100 J, 1.05 μm, 1972
- Shiva: 10 kJ, 1.05 μm, 1978
- Nova: 30 kJ, 351 nm, 1984
- NIF: 1.8 MJ, 351 nm, 2009
Target Designs with Varying Degrees of Risk
Provide Adequate Gain for all Driver Concepts

FI Expt's - Omega, FIREX, HIPER

Tabak Snowmass
The National Ignition Facility (NIF), a nominally 1.8MJ/500TW blue laser being built at Livermore, meets the requirements for ignition

NIF Dedication May 29, 2009

Ignition Campaign - started in 2010
NIF is the World’s first Mega-Joule Facility — 1.3 MJ
Three independent diagnostics measured 2.2 ± 0.2 x 10^14 DT neutrons from an exploding pusher

Laser Energy ~ 1 MJ

<table>
<thead>
<tr>
<th>Observable</th>
<th>Simulations</th>
<th>Experiment (weighted mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield (Cu,Zr activation, MRS)</td>
<td>2-3e14</td>
<td>2.2x10^{14} ± 0.2 x 10^{14}</td>
</tr>
<tr>
<td>Ion Temperature</td>
<td>11-12keV</td>
<td>11.7 ± 0.5 keV</td>
</tr>
<tr>
<td>Bang time</td>
<td>1.90 ± 0.2 ns</td>
<td>1.75 ± 0.15 ns</td>
</tr>
</tbody>
</table>

~600J, Q ~6x10^{-4}
On Sept. 29th at 8:27 p.m. (PDT), NIC conducted the first cryo-layered target experiment on NIF

- All 192-laser beams fired 1 MJ of laser energy into the hohlraum
  - Radiation drive was consistent with earlier shots at this energy (∼290 eV)
  - Preliminary yield estimate was ∼1 x 10^{13} neutrons based on nToF
- The capsule was filled with a mixture of tritium, hydrogen and deuterium tailored to enable the most comprehensive physics results, not to demonstrate ignition
- All systems operated successfully and 26 target diagnostics acquired data

Preliminary results of the target performance are very encouraging, analysis is continuing
This experiment demonstrated ability of the NIC team to conduct layered implosion experiments

- We have successfully fielded a indirect drive layered implosion experiment with thermonuclear fuel [6% D, 22% H, 72% T]
  - Capsules are driven in hohlraums with 288 eV radiation temperature heated by 1 MJ laser energy from 192 smoothed beams on NIF
  - The capsule was shot with a smooth 65 µm thick nuclear fuel layer at 1.5 degrees below the triple point
  - Successfully fielded 11 nuclear and 8 x-ray diagnostics
    - 14.1 MeV DT yield
    - down scattered neutrons (10-12 MeV)
    - Ion temperature $T_{ion}$
    - Capsule Shape and x-ray emission

- Experiments show compression, yield and fuel rho-r consistent with implosions that are not tuned
  - Compressed to 40 microns (x1.5 more than a symcap)
  - Yield of $8 \times 10^{12}$ and 2.8% down scattered neutron fraction x 6 if 50/50 DT => 140J, $Q \sim 1.4 \times 10^{-4}$

The fielding of the first layered capsule implosions has marked the beginning of the ignition campaign on NIF
Lawson Diagram as a Metric for Fusion Progress

Deuterium Plasmas

Deuterium - Tritium Plasmas

Q = W_{Fusion}/W_{Input}
W = energy

Lawson Fusion Parameter, n\tau_i T_e (10^{20} m^{-3} keV s)

Central Ion Temperature (keV)

Q ~ 0.01
Q ~ 0.1
Q ~ 0.1
Q ~ 0.1
Q ~ 0.01
Q ~ 0.001
Q ~ 0.0001
Q ~ 0.0001
Q ~ 0.00001
Q ~ 0.00001
Q ~ 1
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001
Q ~ 0.001

“Reactor Plasma Conditions”
Performance Extension
Proof of Principle
Concept Exploration

Evaluating the Lawson Diagram for Fusion Progress

- Stellarator 1999
- Stellarator 1998
- Stellarator 1996
- T-3 1965
- Reversed Field Pinch (Te) 1998
- Spheromak 1989
- T-3 1968
- Tandem Mirror 1989
- Field Reversed Configuration 1983-91

- NIF
- LMJ
- ITER
- Laser 1986 Direct Drive
- Laser 1996 Direct Drive
- Laser 1986 Indirect Drive
Fusion Energy per Pulse as a Metric for Progress
Average Fusion Power as a Metric for Progress

<table>
<thead>
<tr>
<th>Magnetic Fusion Energy</th>
<th>Inertial Fusion Energy</th>
</tr>
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<tbody>
<tr>
<td><strong>TFTR/JET Actual</strong></td>
<td><strong>NIF Planned</strong></td>
</tr>
<tr>
<td>D-T</td>
<td>First D-T</td>
</tr>
<tr>
<td>1997</td>
<td>~2011</td>
</tr>
<tr>
<td>Fusion Gain, Q</td>
<td>Fusion Gain, Q</td>
</tr>
<tr>
<td>0.3 - 0.65</td>
<td>~10</td>
</tr>
<tr>
<td>Fusion Energy/pulse</td>
<td>Fusion Energy/pulse</td>
</tr>
<tr>
<td>7.5 - 22 MJ</td>
<td>20 MJ</td>
</tr>
<tr>
<td>&lt; Fusion Power&gt;_{Day} (JET)</td>
<td>&lt; Fusion Power&gt;_{Day} (ITER)</td>
</tr>
<tr>
<td>~5,000 W</td>
<td>~100 MW</td>
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<tr>
<td>&lt; Fusion Power&gt;_{Day} (TFTR)</td>
<td>~70 W</td>
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<tr>
<td>~5,000 W</td>
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<tr>
<td>&lt; Fusion Power&gt;_{Day} (ITER)</td>
<td>~70 W</td>
</tr>
<tr>
<td>~100 MW</td>
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dmeade: 2010
This is Not a Fast Track to Fusion Energy - this is too Slow

Key Decisions:
- IFE IREs
- MFE PEs
- IFMIF
- MFE or IFE
- Demo

Decision - IFE or MFE or No FE
The Fusion in a Decade Challenge

Major technical advances have been made in a Decade

Lunar Landing: 7 Years
(Kennedy speech to Armstrong lands)

Nuclear Submarine: 6 Years
(Rickover starts to Nautilus sails)

J. Sethian 2003

• What could be done in the next decade to increase the credibility of fusion?
Concluding Thoughts

• By any measure both magnetic and inertial fusion have made enormous progress during the past 50 years, and have established a solid technical basis for taking the next step(s) to burning plasmas.

• However, large gaps in burning plasma science and huge gaps in fusion technology still remain to be overcome before either magnetic or fusion energy can become a practical energy source.

• IFE has an ambitious plan to address their remaining issues for the development of fusion energy.

• “Old” plan for MFE envisions a very long time scale that may not be sustainable. It is time for some soul searching and development of a more attractive plan for MFE.
• Logic III became the basis for the MFE Act of 1980.
• The US Fusion Program evolved on to Logic I - we never get there.