50 Years of Fusion Research

Dale Meade
Fusion Innovation Research and Energy®
Princeton, NJ

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San Diego, CA 92101
Path of Progress for Fusion Energy Science

... developing safe uses of atomic energy
Fusion Prior to Geneva 1958

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

- Controlled Thermonuclear Fusion had great potential
  - Uncontrolled Thermonuclear fusion demonstrated in 1952
  - 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 reactors - Thomson, Tamm/Sakharov, Spitzer

- Reality began to set in by the mid 1950s
  - Collective effects - MHD instability (1954)
  - Strong fluctuations and Bohm diffusion were 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
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
  - 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
  - Several levitated superconducting multipoles built 1970-74(LSP,LNL-Lev, Cul Lev, FM-I) were used to study connection between turbulence and transport.
  - Confinement gradually increased from $1 \tau_B$ to 300 $\tau_B$ for low temp plasmas
Stabilization of MHD Interchange by Geometry (minimum |B|) in a Mirror Machine

Increasing $B_{\text{multipole}}$

Well Formed

Fig. 8: Oscillograms of ion current entering a Langmuir probe placed at various distances from the axis of the trap. (The figures in the right-hand corners of each oscillogram are the sweep lengths in milliseconds.)

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

![Graph showing Thomson scattering results.](image)

- 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.

Symmetric Tokamak (ST)
1970

Model C Stellarator
1969
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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, $I_p$, $n$, $T$,........
- Auxiliary heating (compression, ICRF, NBI, ECRH, LH )
- Current Drive (LH, NBI, ... )
- Impurity control (limiters, divertors)
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.

- Four Large Tokamaks approved for construction less than a decade after T-3
- TFTR conservative physics/strong aux heating const began 1976
- 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   =>    3MA to 7MA

**Plasma Volume**

- $1 m^3$   =>  35 $m^3$ to 100 $m^3$

**Auxiliary Heating**

- 0.1 MW  =>  20 MW to 40 MW

J. Willis, MacFusion
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<th>Initial Value</th>
<th>=&gt;</th>
<th>Final Value</th>
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<td>0.3 MA</td>
<td>=&gt;</td>
<td>3 MA to 7 MA</td>
</tr>
<tr>
<td>Plasma Volume</td>
<td>1 m³</td>
<td>=&gt;</td>
<td>35 m³ to 100 m³</td>
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<tr>
<td>Auxiliary Heating</td>
<td>0.1 MW</td>
<td>=&gt;</td>
<td>20 MW to 40 MW</td>
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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 1978, $T_i \approx 5.8 \text{ keV}$ was achieved in a collisionless plasma reducing concerns about Trapped Ion instabilities. $T_i$ was increased to 7 keV in 1980.

- 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 $\tau_E \sim n a^2$. 
- 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

\[ P_{\text{NBI}} = 2.6 \text{ MW H in D} \]
\[ B_0 = 2.2 \text{ T} \]
\[ I_p = 320 \text{ kA} \]
Configuration: \( \text{SN}^+ \)

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

F. Wagner, IPP
Four Large Tokamaks Completed in 1980s

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

After about 9 years, T-15 completed.
Large Tokamaks Extend Plasma Parameters

- By the mid 80s, after 4 years of operation the plasma parameter range had been significantly extended
  - $T_i \sim 20$ 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 $T_i \sim 1.5$ 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, RF heating, pellet injection, plasma facing components
Significant Fusion Power (>10MW) Produced in 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
  - 3 years of operation with DT, and then decommissioned.

- **Advanced Tokamak Mode Employed for High Performance**
  - Improved ion confinement TFTR, DIII-D, $Q_{DTequiv} \sim 0.3$ in DIII-D 1995
  - $n\tau_E T$ record => $Q_{DTequiv}$ 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 (Also TSTA)
  - Remote handling

More than 10 years ago
Fusion Temperatures Attained,
Fusion Confinement One Step Away

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

\[ n_i(0)\tau_E T_i \]
increased by \( \sim 10^7 \) since 1958
The Next Step Burning Plasmas

- 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

- 1984 - Tokamak Fusion Core experiment (TFCX), SC coils, 200 MW, ss 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 (1985-1989)
CIT PARAMETERS AND OPERATIONAL LIMITS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TOKAMAK</th>
<th>POWER SUPPLIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius</td>
<td>2.1 m</td>
<td></td>
</tr>
<tr>
<td>Minor Radius</td>
<td>0.65 m</td>
<td></td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td>Elongation (95% surface)</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Field on axis</td>
<td>10 T*</td>
<td>7 T</td>
</tr>
<tr>
<td>Current @ $\alpha = 3.1$</td>
<td>11 MA</td>
<td>7.7 MA</td>
</tr>
<tr>
<td>Neutron Wall Loading @ 0.8 Beta Limit</td>
<td>6.0 MW/m$^2$</td>
<td></td>
</tr>
<tr>
<td>TF Flat-Top Time</td>
<td>5 sec</td>
<td></td>
</tr>
<tr>
<td>Ohmic Heating</td>
<td>54 Volt-sec.</td>
<td></td>
</tr>
<tr>
<td>Energy/Peak Power</td>
<td>11.9 GJ/1300 MW</td>
<td>6.2 GJ/600 MW</td>
</tr>
</tbody>
</table>

*A limited number of 11 T discharges is also available.*
Based on today’s understanding, CIT would have “ignited” with $Q = 35$ using a conservative $H_{98}(y,2) = 0.92$ !!!!
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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

- 2003 - US joins ITER as one of seven partners
ITER Construction is Now Underway

ITER Site Under Construction

Reactor scale

First Plasma planned for 2018
First DT operation planned for ~2022
ITER Construction is Now Underway

ITER Site Under Construction

Reactor scale

First Plasma planned for 2018

First DT operation planned for ~2022 ⟷ 2027?
Is ITER Sufficient to Resolve Burning-Plasma Issues for DEMO?

**High Fusion Gain** - attain good confinement with profiles defined by alpha heating ($P_\alpha/P_{\text{ext}} = Q/5$), possible non-linear dependence of transport on gradients, coupled to edge plasma by pedestal, optimum temperature for fusion $\sim 15$ keV and high density but efficient current drive favors higher $T \sim 30$ keV and lower density.

**Sustainment (100% NI)** - produce large bootstrap current with pressure profiles defined by alpha heating and residual current driven efficiently by low power $P_{cd} \leq 5P_\alpha/Q$.

**High Fusion Power Density** ($\beta^2 B^4 <\sigma v>/T^2$) - to provide high neutron wall loading. Can near optimum $\beta$ be attained for alpha-defined profiles?

**Plasma Control** ($P_{cd} + P_{\text{cont}} = 5P_\alpha/Q$) - maintain plasma control (esp. disruptions) with low power typically $< 0.15P_\alpha$. Will a burning plasma evolve to a self-organized state with good confinement, high bootstrap and high $\beta$?

**Exhaust Power Density** - can high exhaust power densities be handled while maintaining edge plasma for high $Q$ and efficient CD with long PFC lifetime?

**Self-Conditioned PFCs** - will the PFCs self-condition that is consistent with high $Q$ and $\beta$, and long PFC lifetime?
High-Performance Steady-State Burning-Plasma Metrics and Gaps from ITER to DEMO

<table>
<thead>
<tr>
<th>Table I. Individual Issue (Metric)</th>
<th>Today* (&lt;10τ_E)</th>
<th>ITER</th>
<th>ARIES-I</th>
<th>ARIES-AT</th>
<th>&lt;Gap&gt; IT to AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion Gain (Q)</td>
<td>&lt; 0.2</td>
<td>5</td>
<td>20</td>
<td>50</td>
<td>7</td>
</tr>
<tr>
<td>Self-heating (P_α/P_ex)</td>
<td>0.04</td>
<td>1</td>
<td>4</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Sustainment (100% NI)** (P_cd/P_α)</td>
<td>&gt;25</td>
<td>1</td>
<td>0.25</td>
<td>0.1</td>
<td>6</td>
</tr>
<tr>
<td>Current Drive fraction (1-f_0s) (%)</td>
<td>~30</td>
<td>~50</td>
<td>32</td>
<td>9</td>
<td>2.5</td>
</tr>
<tr>
<td>Neutron Wall Loading (MWm⁻²)</td>
<td>0.1</td>
<td>0.5</td>
<td>2.5</td>
<td>3.3</td>
<td>6</td>
</tr>
<tr>
<td>Plasma Pressure (atm)</td>
<td>1.6</td>
<td>2.5</td>
<td>10</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Fusion Power density (MWm⁻³)</td>
<td>0.3</td>
<td>0.5</td>
<td>4</td>
<td>4.7</td>
<td>8</td>
</tr>
<tr>
<td>Plasma Control* (P_cont/P_α)</td>
<td>&gt;25</td>
<td>1</td>
<td>0.25</td>
<td>0.1</td>
<td>6</td>
</tr>
<tr>
<td>Exhaust Power Density (P_e/A_{out} (MWm⁻²)</td>
<td>0.85</td>
<td>0.2</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Self-Condition PFCs &amp; FW f(t_{pulse}, T, φ)</td>
<td>No</td>
<td>?</td>
<td>Yes</td>
<td>Yes</td>
<td>?</td>
</tr>
</tbody>
</table>

* Not all simultaneous
** Current Drive Power + Plasma Control Power = 5 P_α/Q
Assumes ITER will be upgraded with addition of Lower Hybrid current drive for Scenario 4.

- ARIES-I And ARIES-AT span the range of a possible DEMO.

- Individual gaps between ITER (scenario 4) and ARIES range between 2.5 and 10
Inertial Confinement Fusion, Early Days

- 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.
• Classified Centurion-Halite nuclear tests in ~1986 are reported to have validated compression modeling.

• Many aspects of US ICF declassified in Nov 1994, allowing target designs to be discussed.

• Omega Project achieves gain of 0.01 using direct drive of a DT capsule in 1996.

• Fast Ignitor concept (1995) offers possibility of reduced driver energies.

• There has been dramatic progress in driver intensity and pellet fabrication in the past 40 years, and many challenges remain.

• Multiple paths in drivers (Glass, KrF, Z-pinch) are being pursued.
• Glass laser energy has increased $10^6$

• Fusion energy will need:
  - increased efficiency
  - increased repetition rate
Target Designs with Varying Degrees of Risk Provide Adequate Gain for all Driver Concepts

Fl Expt's - Omega, FIREX, HIPER

Tabak Snowmass
Target Designs with Varying Degrees of Risk
Provide Adequate Gain for all Driver Concepts

FI Expt's - Omega, FIREX, HIPER

Tabak Snowmass
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Fl Expt’s - Omega, FIREX, HIPER
NIF Ready to Begin Ignition Campaign

NIF Groundbreaking May 29, 1997

NIF Dedication May 29, 2009

Ignition Campaign - starting 2010
Some Overall Highlights

- A strong scientific basis has been established for fusion.
- Diagnostics and Plasma Technology (Aux heating, CD, pellet inj) enabled progress.
- Computer Simulations are becoming more realistic and integral to analysis and prediction.
- Several promising paths to fusion, each working on optimization and sustainment.
- Temperatures needed for fusion achieved - in many facilities.
- Confinement needed for fusion is being approached - one step away.
- Complex fusion systems have been operated at large scale.
- Fusion systems using fusion fuel (DT) operated safely.
- Fusion could move much faster if required resources were applied.
- Now on the threshold of energy producing plasmas in both magnetic and inertial fusion.
Facilities to Produce Fusion Energy are under Construction
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- **ITER**
  - Magnetic Fusion Energy

- **NIF**
  - Inertial Fusion Energy
  - First D-T: ~2010
  - Fusion Gain, Q: 10 - 20
  - Fusion Energy/pulse: 40 MJ
Facilities to Produce Fusion Energy are under Construction

**ITER**
- First D-T: ~2027?
- Fusion Gain, Q: 10
- Fusion Energy/pulse: 200,000 MJ

**NIF**
- First D-T: ~2010
- Fusion Gain, Q: 10 - 20
- Fusion Energy/pulse: 40 MJ
NIF and ITER will Extend Progress in Fusion Energy
Fission-Fusion in 1 Decade
Fission-Fusion in 1 Decade

- First D-T: ~2020
- Fusion Gain, Q: 25
- Fusion Power: 400 MW
- Fission + Fusion Power: 2,500 MW
Fission-Fusion in 1 Decade

<table>
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Fusion in 3 Decades

DEMO
Fission-Fusion in 1 Decade

- First D-T ~2020
- Fusion Gain, Q 25
- Fusion Power 400 MW
- Fission + Fusion Power 2,500 MW

Fusion in 3 Decades

- First D-T Power ~2025+15
- Fusion Gain, Q 20 - 45
- Fusion Power 2,500 MW
Concluding Thoughts
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- By any measure magnetic and inertial fusion have made enormous progress during the past 50 years, and each has established a solid technical basis for taking the next step(s) to burning plasmas.
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• A comprehensive long range plan is needed for the US magnetic fusion energy program!!