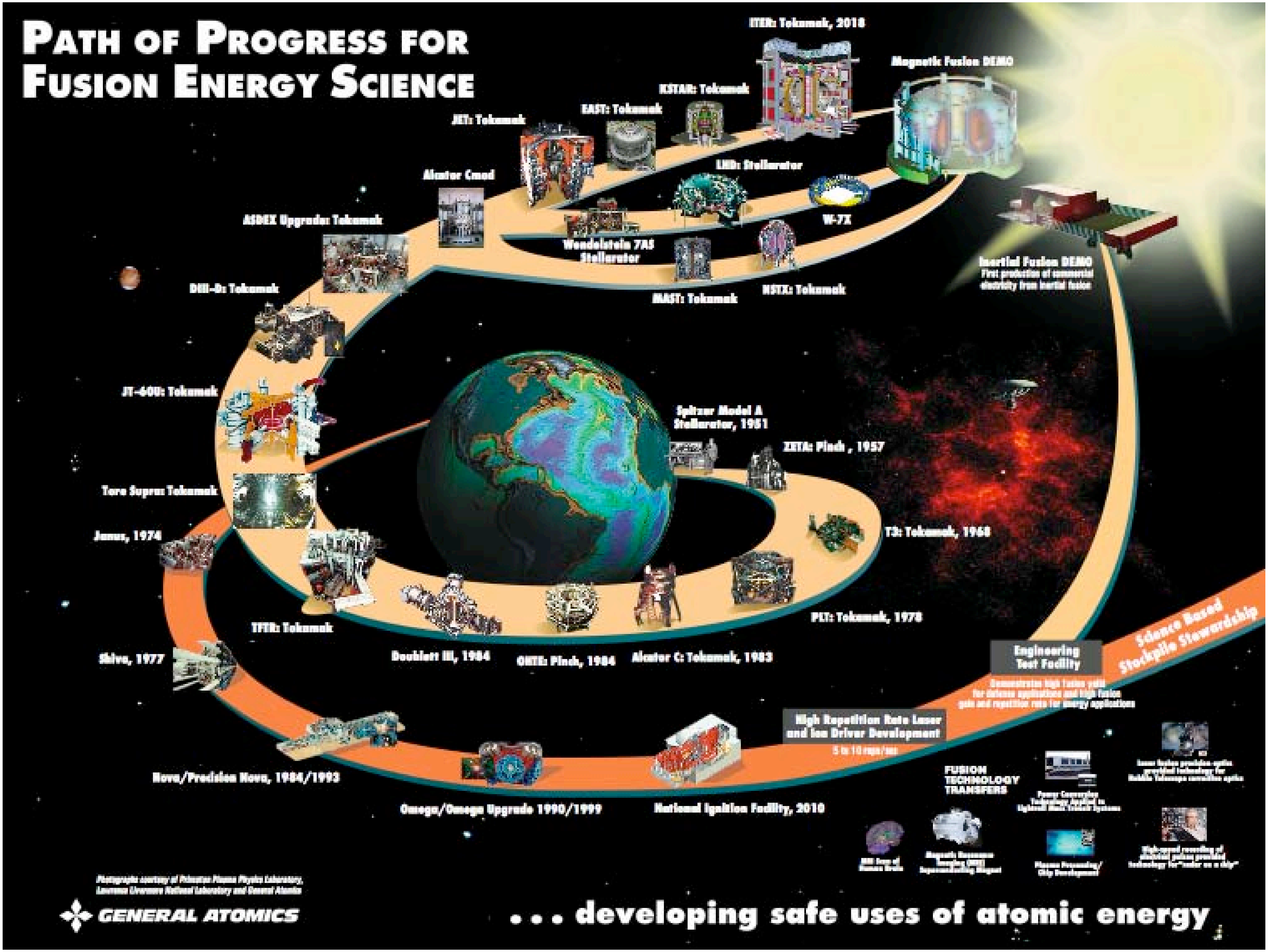
50 Years of Fusion Research

Dale Meade
Fusion Innovation Research and Energy®
Princeton, NJ

SOFE 2009
June 1, 2009
San Diego, CA 92101


PATH OF PROGRESS FOR FUSION ENERGY SCIENCE
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FUSION TECHNOLOGY TRANSFERS
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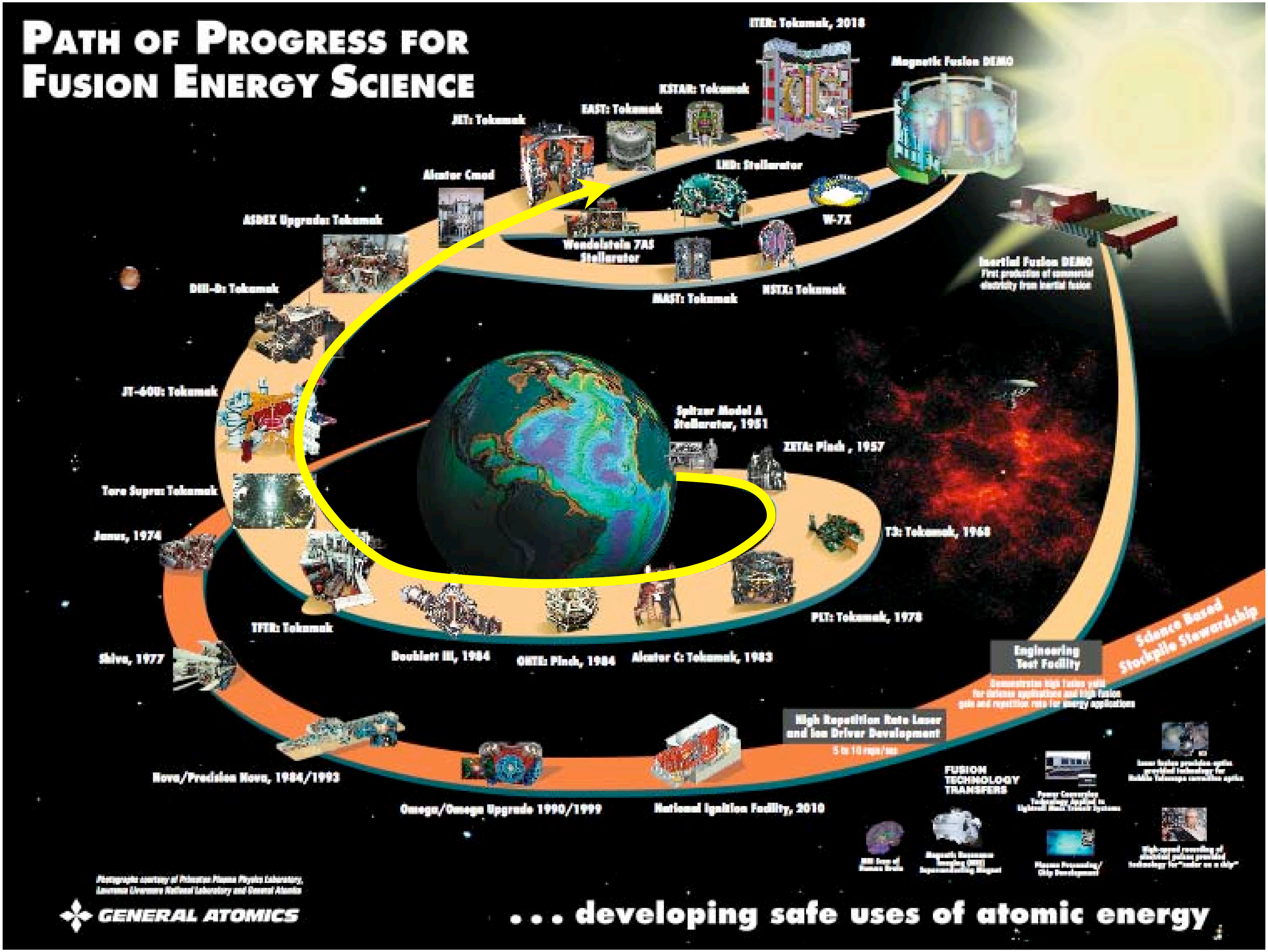
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Fusion Prior to Geneva 1958

- 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 fluctations 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 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 mulitpoles built 1970-74(LSP,LNL-Lev, Cul Lev, FM-I) were used to study connection between turbulence and transport.
  - Confinement gradually increased from 1 τ_B to 300 τ_B for low temp plasmas

Stabilization of MHD Interchange by Geometry (minimum |B|) in a Mirror Machine

Increasing $B_{multipole}$

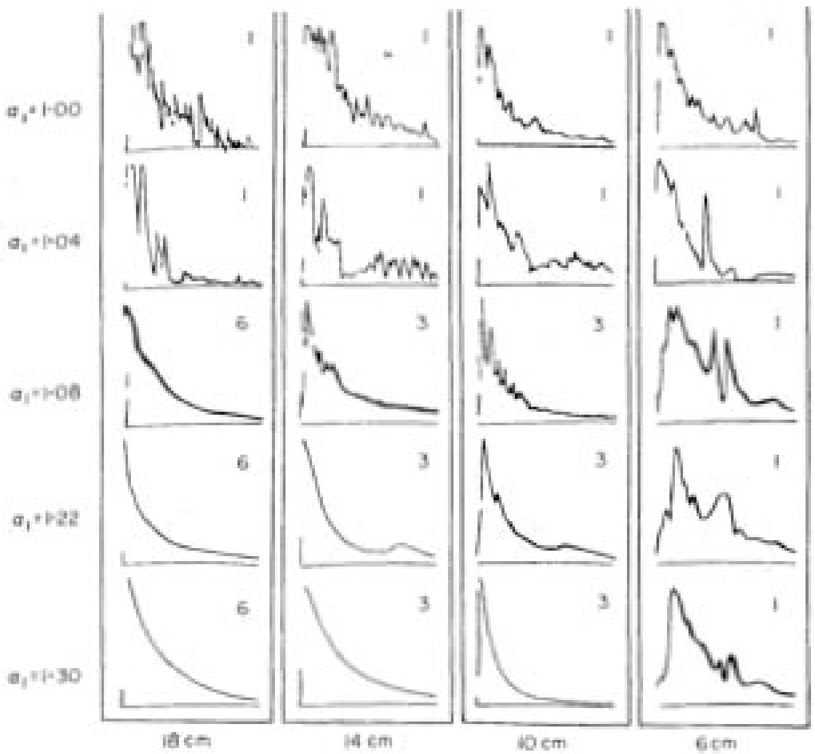
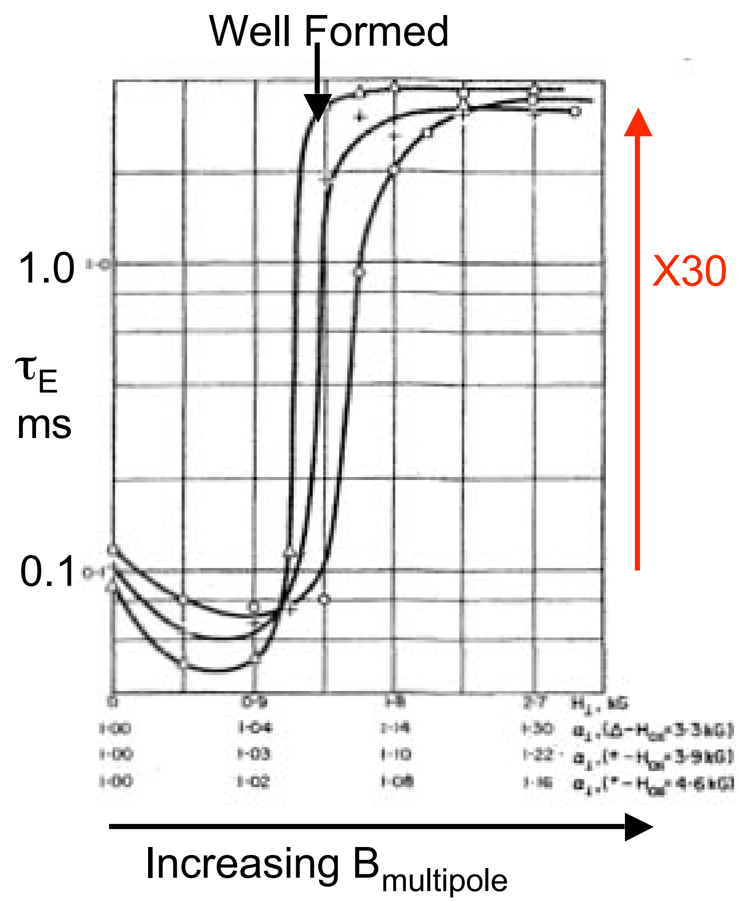


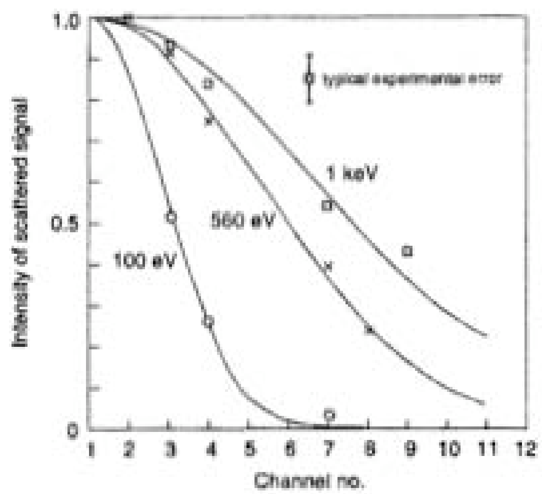
FIG. 8.—Oscillograms of ion current entering a Langmuir probe placed at various distances from the axis of the trap. (The figures in the right-hand corners of each oscillogram are the sweep lengths in milliseconds.)



- IOFFE IAEA Salzburg 1961, J Nuc Energy Pt C 7, p 501 1965

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

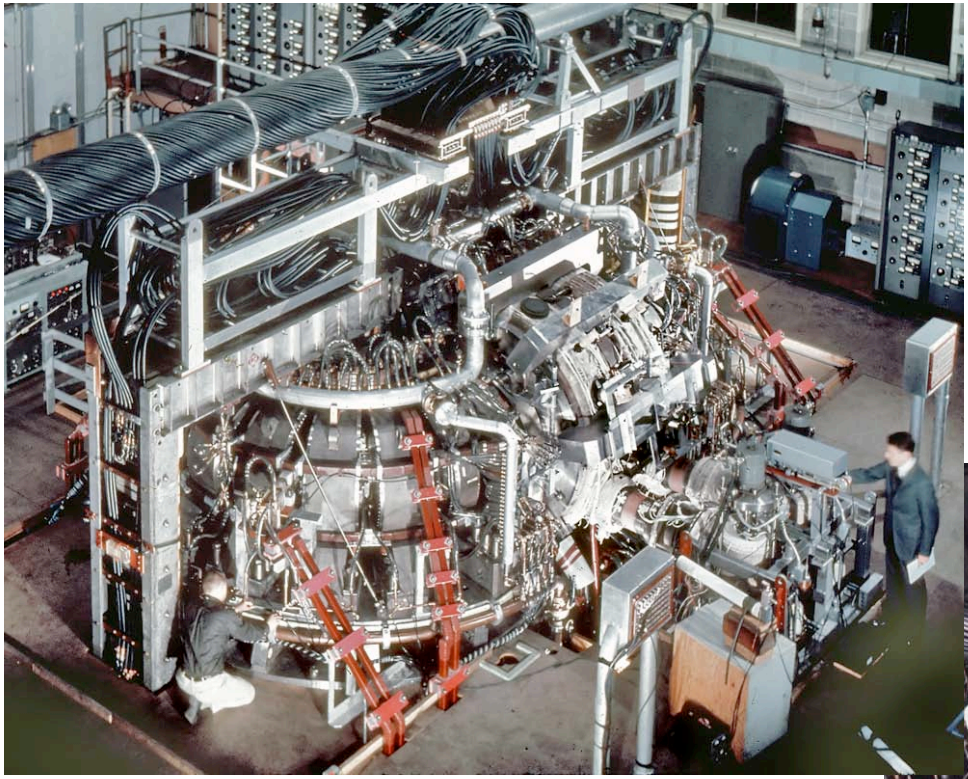


From Braams and Stott

- Energy confinement ≈ 30 τ_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.

40 years ago

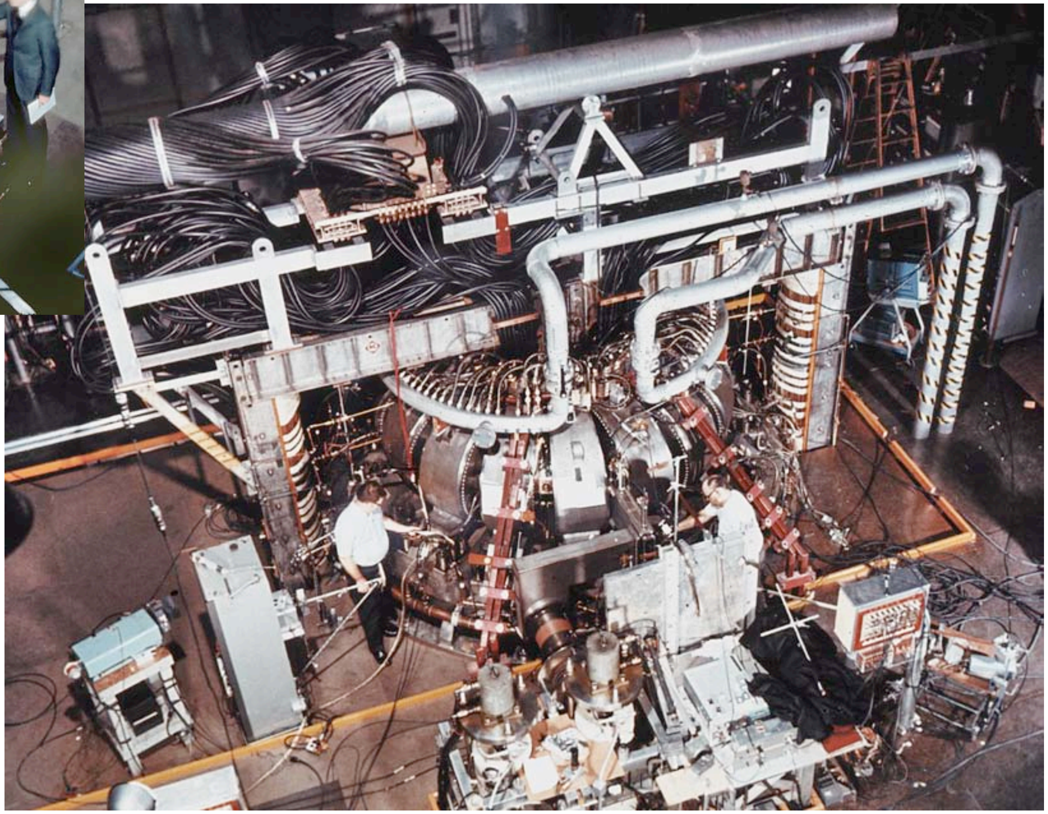
Model C Stellarator Converted to Tokamak in 6 months



Model C Stellarator
1969

T-3 results are quickly reproduced and extended.

Symmetric Tokamak (ST)
1970



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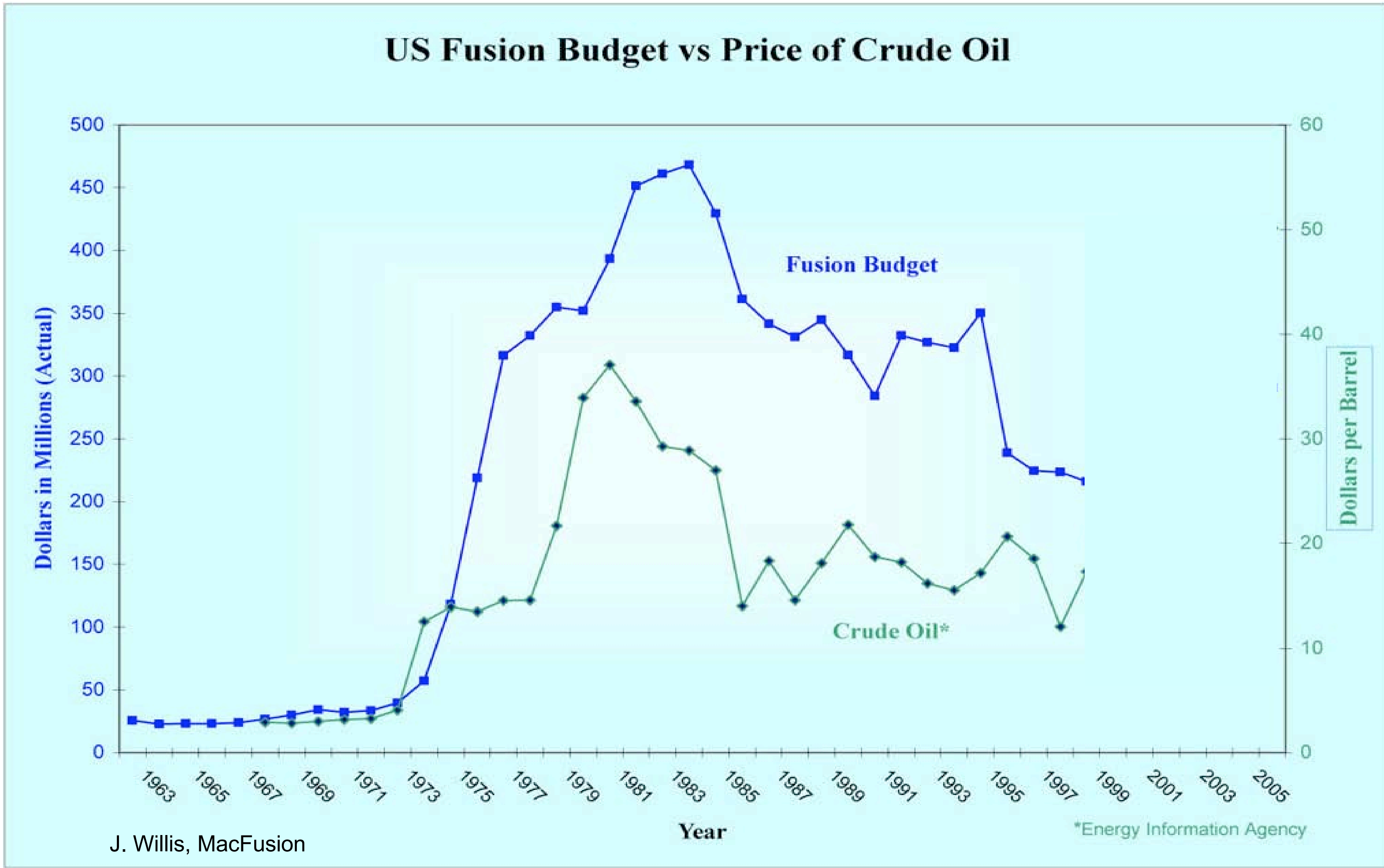
- Hints of a major advance at IAEA Novosibirsk 1968, but skeptics abound
- Thomson Scattering (Peacock/Robinson) Dubna 1969 confirms $T_e \approx 1$ keV
- Energy confinement ≈ 30 τ_B - Bohm barrier broken for a hot plasma
- Skeptics converted to advocates overnight, Model C Stellarator converted to Symmetric 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,.......
  - Auxiliary heating (compression, ICRF, NBI, ECRH, LH)
  - Current Drive (LH, NBI, ...)
  - Impurity control (limiters, divertors)

40 years ago

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.



J. Willis, MacFusion

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.

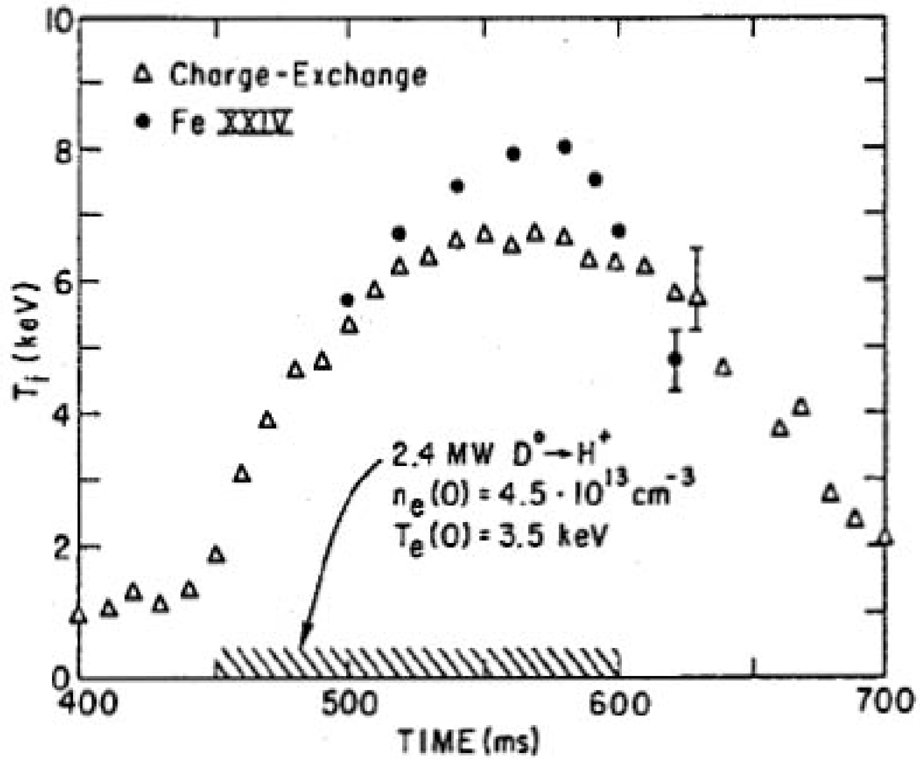
- Four Large Tokamaks approved for construction less than a decade after T-3
  - TFTR conservative physics/strong aux heating const began 1976
  - JET shaped plasma - const began 1977
  - JT-60 poloidal divertor- const began 1978
  - T-15 Superconducting TF (NbSn) const began 1979

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

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.

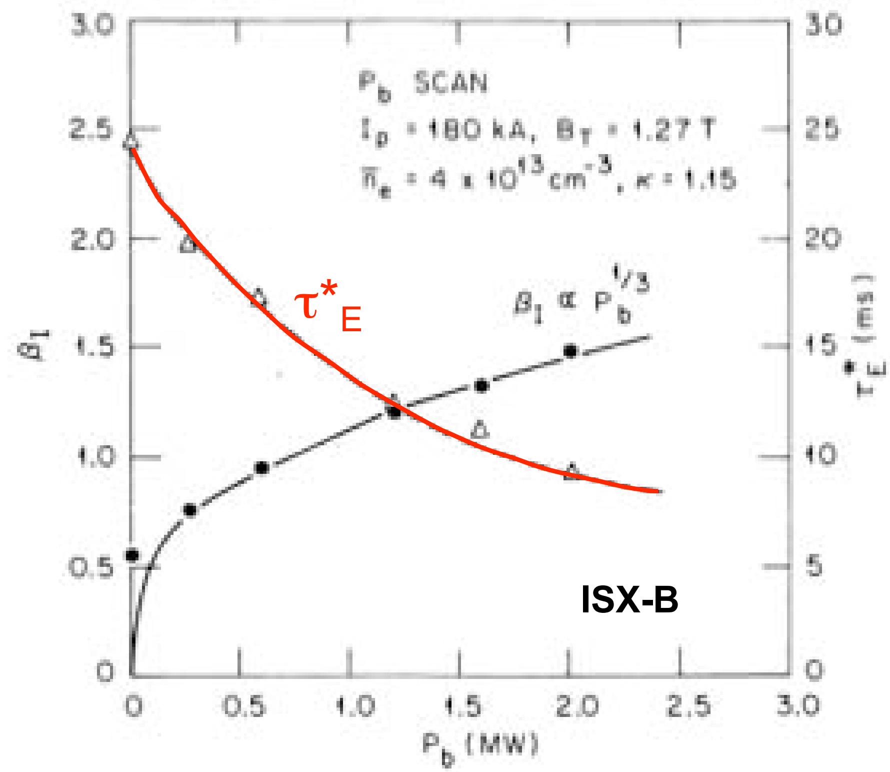


30 years ago

- In 1978, T_i ~ 5.8 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 $n\tau_E \approx 1.5 \times 10^{19}\ m^{-3}\ s$, consistent with optimistic scaling $\tau_E \sim na^2$.

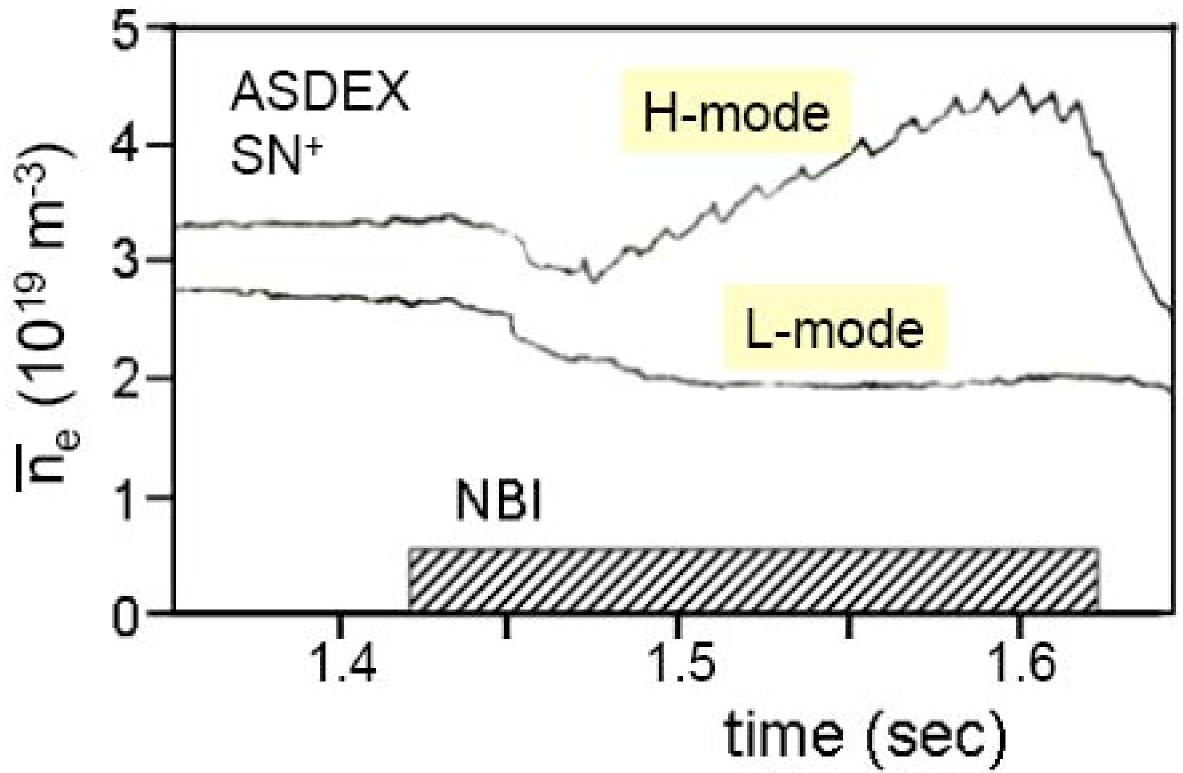
Auxiliary Heating Reveals New Trends 1981



- Auxiliary heating allowed controlled experiments to reveal the scaling of the global 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



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

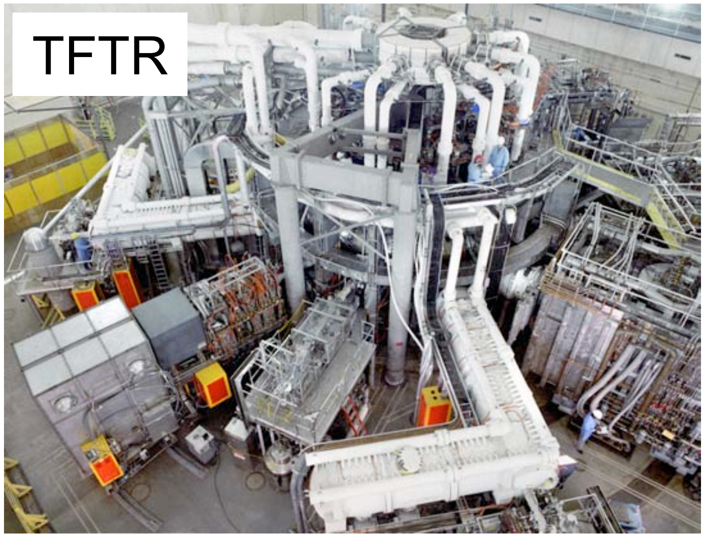
Two branches:

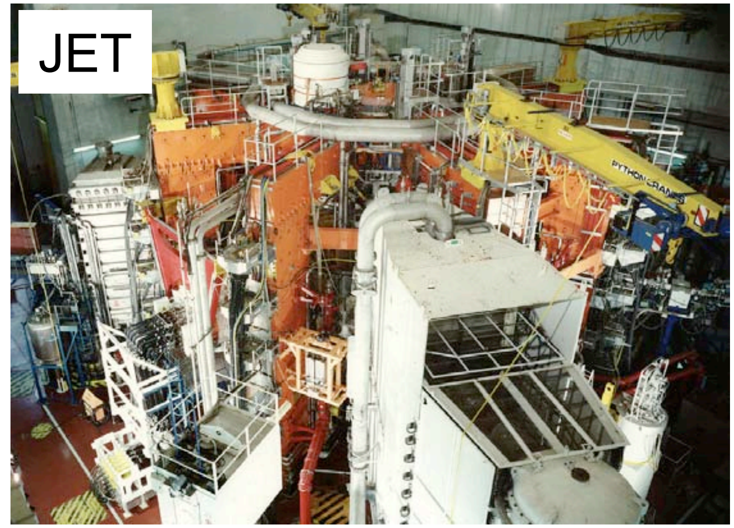
Type „a": L-mode
Type „b": H-mode

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

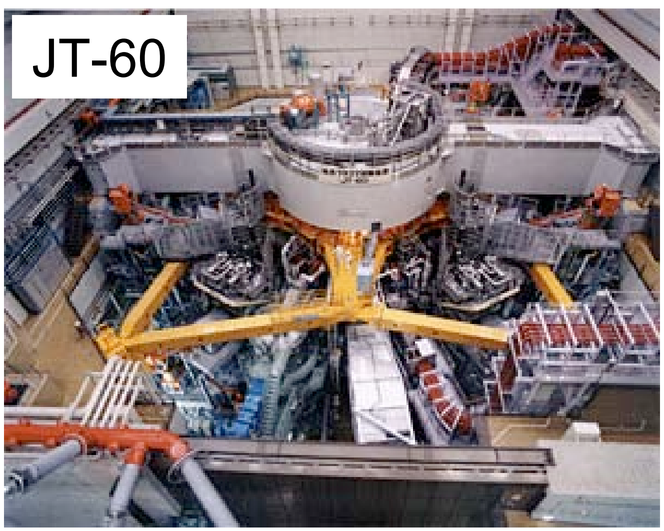
F. Wagner, IPP

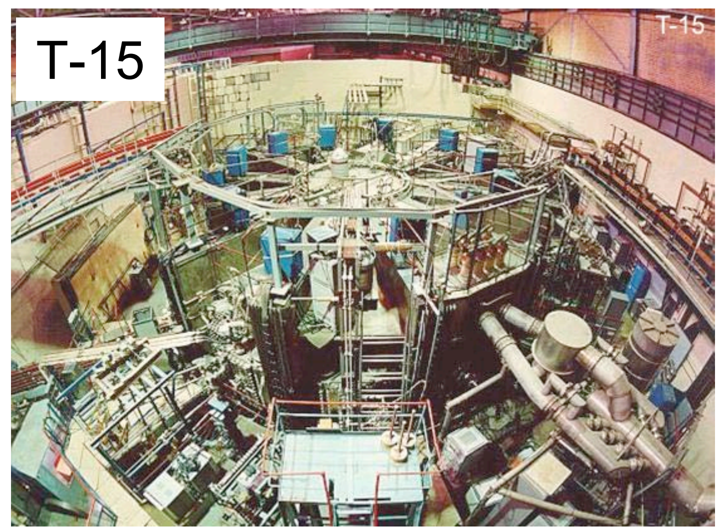
Four Large Tokamaks Completed in 1980s





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~ 20 keV and $n_e(0)\tau_E$ ~ 1.5×10^{19} m^{-3} s with neutral beam injection
  - $n_e(0)\tau_E$ ~ 1.5×10^{20} m^{-3} s and T_i~ 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

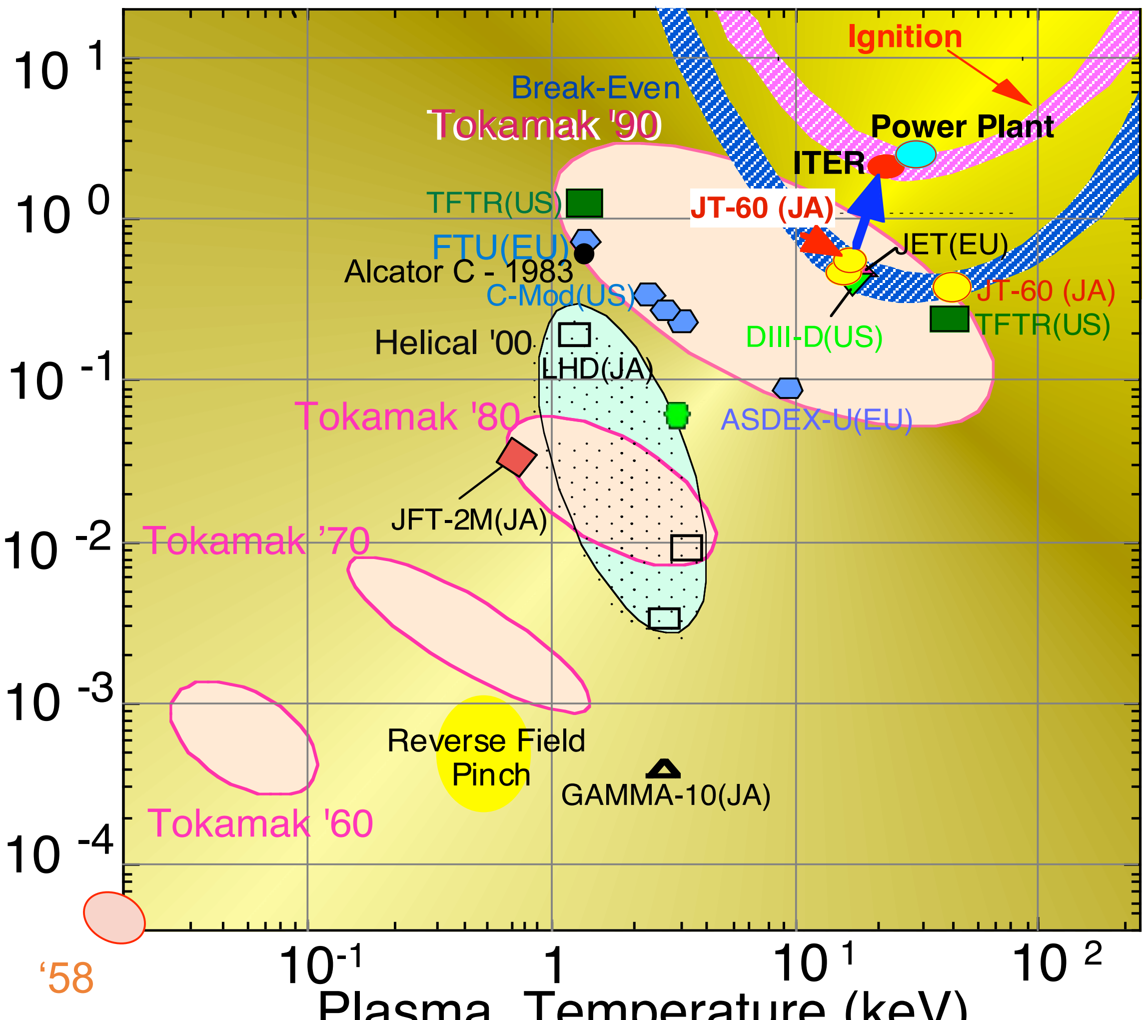
More than 20 years ago

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, $Q_{DTequiv}$ ~ 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} m^{-3} s)

$n_i(0)\tau_E T_i$ increased by $\sim 10^7$ since 1958

JAEA

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

	TOKAMAK	POWER SUPPLIES
MAJOR RADIUS	2.1 M	
MINOR RADIUS	0.65 M	
ASPECT RATIO	3.25	
ELONGATION (95% SURFACE)	2.0	
FIELD ON AXIS	10 T*	7 T
CURRENT @ q = 3.1	11 MA	7.7 MA
NEUTRON WALL LOADING @ 0.8 BETA LIMIT	6.0 MW/M^2	
TF FLAT-TOP TIME	5 SEC	
OHMIC HEATING	54 VOLT-SEC.	
ENERGY/PEAK POWER	11.9 GJ/1300 MW	6.2 GJ/600 MW

*A LIMITED NUMBER OF 11 T DISCHARGES IS ALSO AVAILABLE.

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Based on today's understanding, CIT would have "ignited" with Q = 35 using a conservative H98(y,2) = 0.92 !!!!

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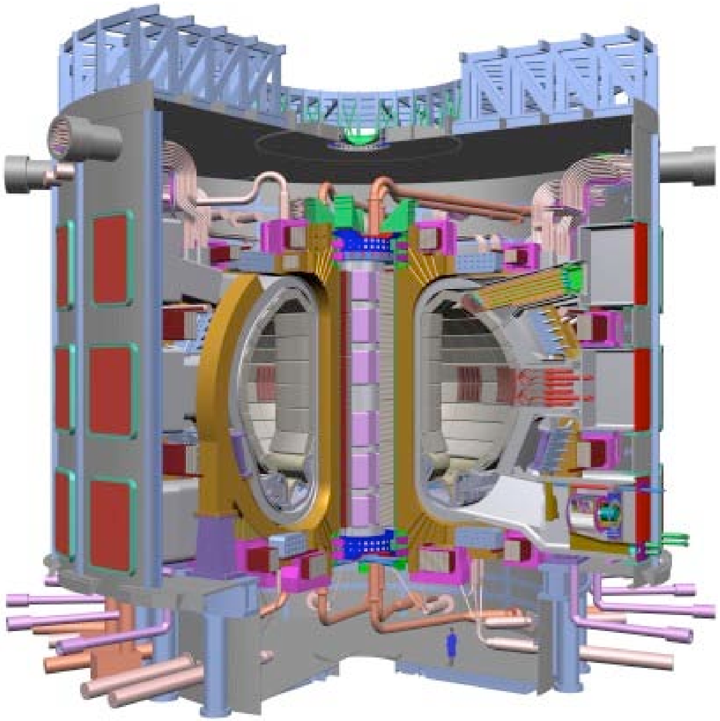
- → 1990 - BPX a larger CIT with less ambitious goals and higher cost was put forward - cancelled in Sept 1991(SEAB, Townes Panel) on to TPX
- 1992 - ITER - US joins ITER as one of four partners, has Lead Design Center
- 1997 - US leaves ITER after completion of Engineering Design Activity
- 1998 - US initiates study of advanced CIT called FIRE
- 2003 - US joins ITER as one of seven partners

ITER Construction is Now Underway



Reactor scale

ITER Site Under Construction

First Plasma planned for 2018

First DT operation planned for ~2022

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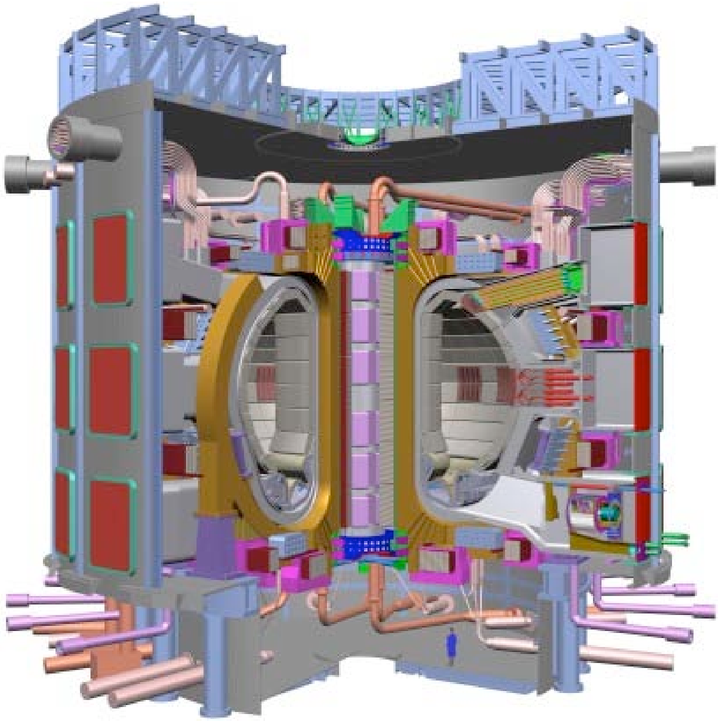

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ITER Site Under Construction

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($P_{\alpha}/P_{ext} = Q/5$), possible non-linear dependence of transport on gradients, coupled to edge plasma by pedestal, optimum temperature for fusion ~ 15 keV and high density but efficient current drive favors higher T ~ 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 ($\beta^2 B^4 \langle\sigma v\rangle/T^2$) - to provide high neutron wall loading. Can near optimum β be attained for alpha-defined profiles?

Plasma Control ($P_{cd} + P_{cont} = 5P_{\alpha}/Q$) - 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 β?

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 β, and long PFC lifetime?

High-Performance Steady-State Burning-Plasma Metrics and Gaps from ITER to DEMO

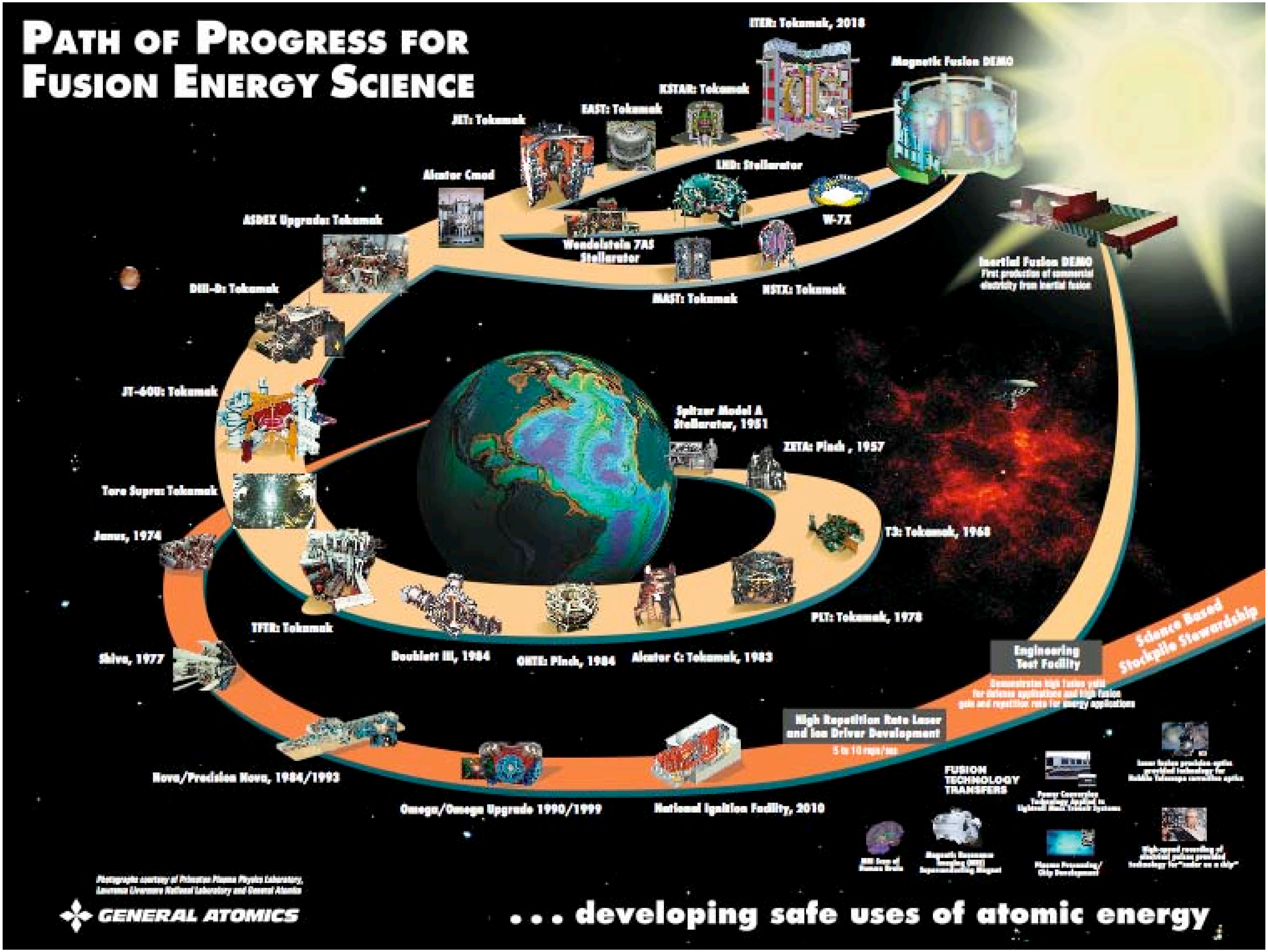
Table I. Individual Issue (Metric)	Today* ($>10\tau_E$)	ITER	ARIES-I	ARIES-AT	<Gap> IT to AR
Fusion Gain (Q)	< 0.2	5	20	50	7
Self-heating (P_α/P_{ext})	0.04	1	4	10	7
Sustainment (100% NI)** (P_{cd}/P_α)	>25	1	0.25	0.1	6
Current Drive fraction ($1-f_{bs}$) (%)	~30	~50	32	9	2.5
Neutron Wall Loading (MWm^{-2})	0.1	0.5	2.5	3.3	6
Plasma Pressure (atm)	1.6	2.5	10	10	4
Fusion Power density (MWm^{-3})	0.3	0.5	4	4.7	8
Plasma Control* (P_{cont}/P_α)	>25	1	0.25	0.1	6
Exhaust Power Density (P_{heat}/A_{ps} (MWm^{-2})	0.85	0.2	1	1	5
Self-Condition PFCs & FW f(t_{pulse}, T, ϕ,	No	?	Yes	Yes	?

* 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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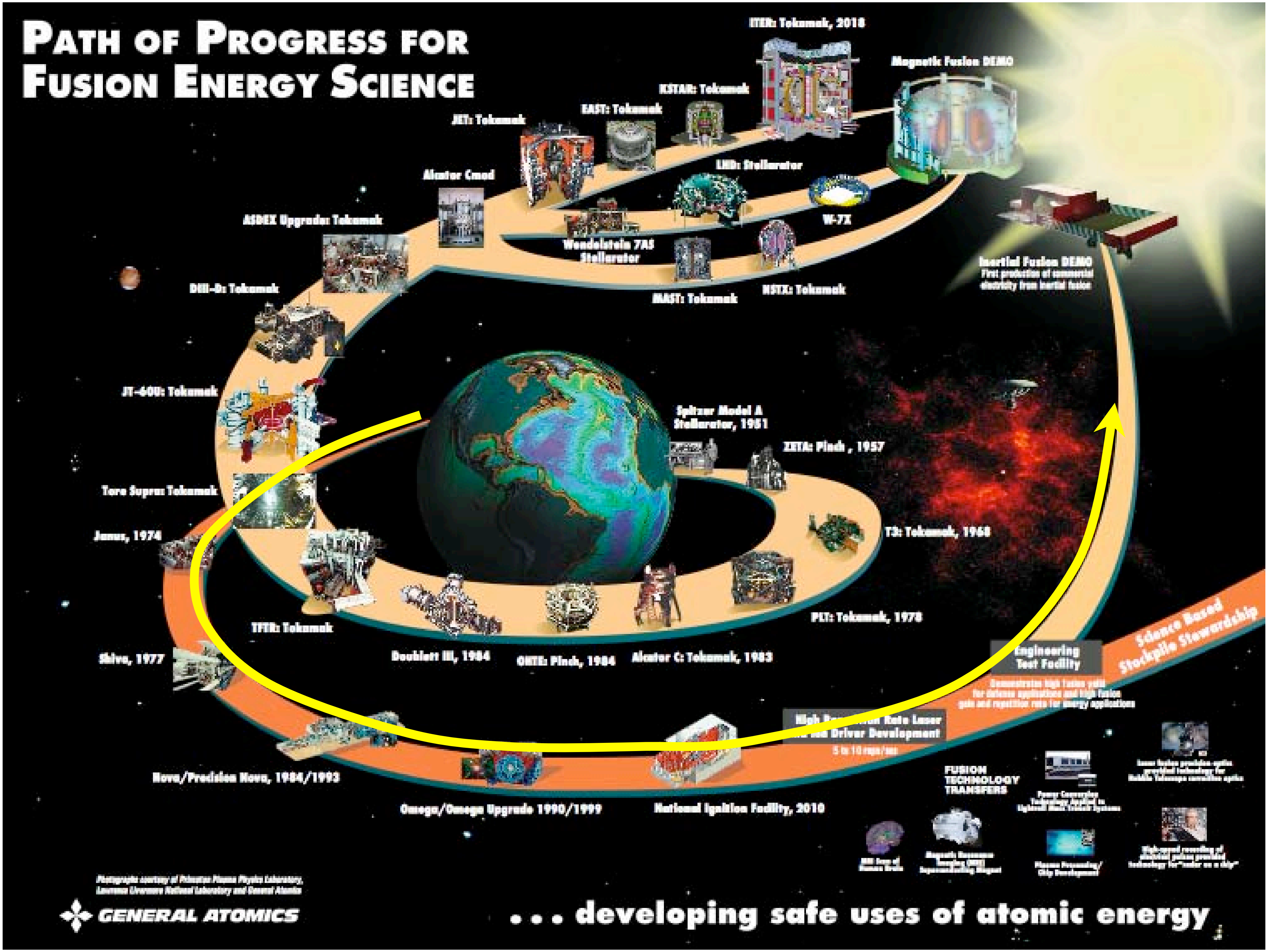
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Inertial Confinement Fusion, Early Days

- 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.
- 1972- Nature article by Nuckolls et al with computer modeling of laser driven compression *Nature* Vol. 239, 1972, pp. 129
- 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.

Construction of NIF/LMJ - ICF Burning Plasmas

- 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.

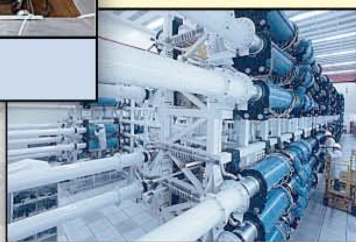
NIF Enabled by Rapid Advance in Laser Technology

Janus

1972

100 J
1.05 μm

Shiva



1978

10 kJ
1.05 μm

Nova

1984

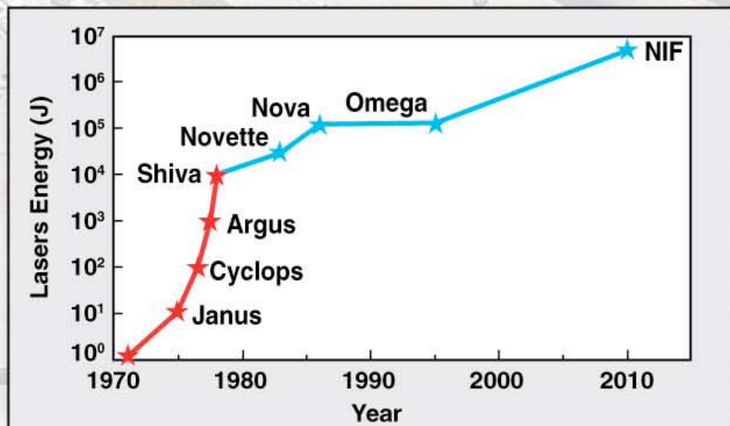
30 kJ
351 nm

NIF

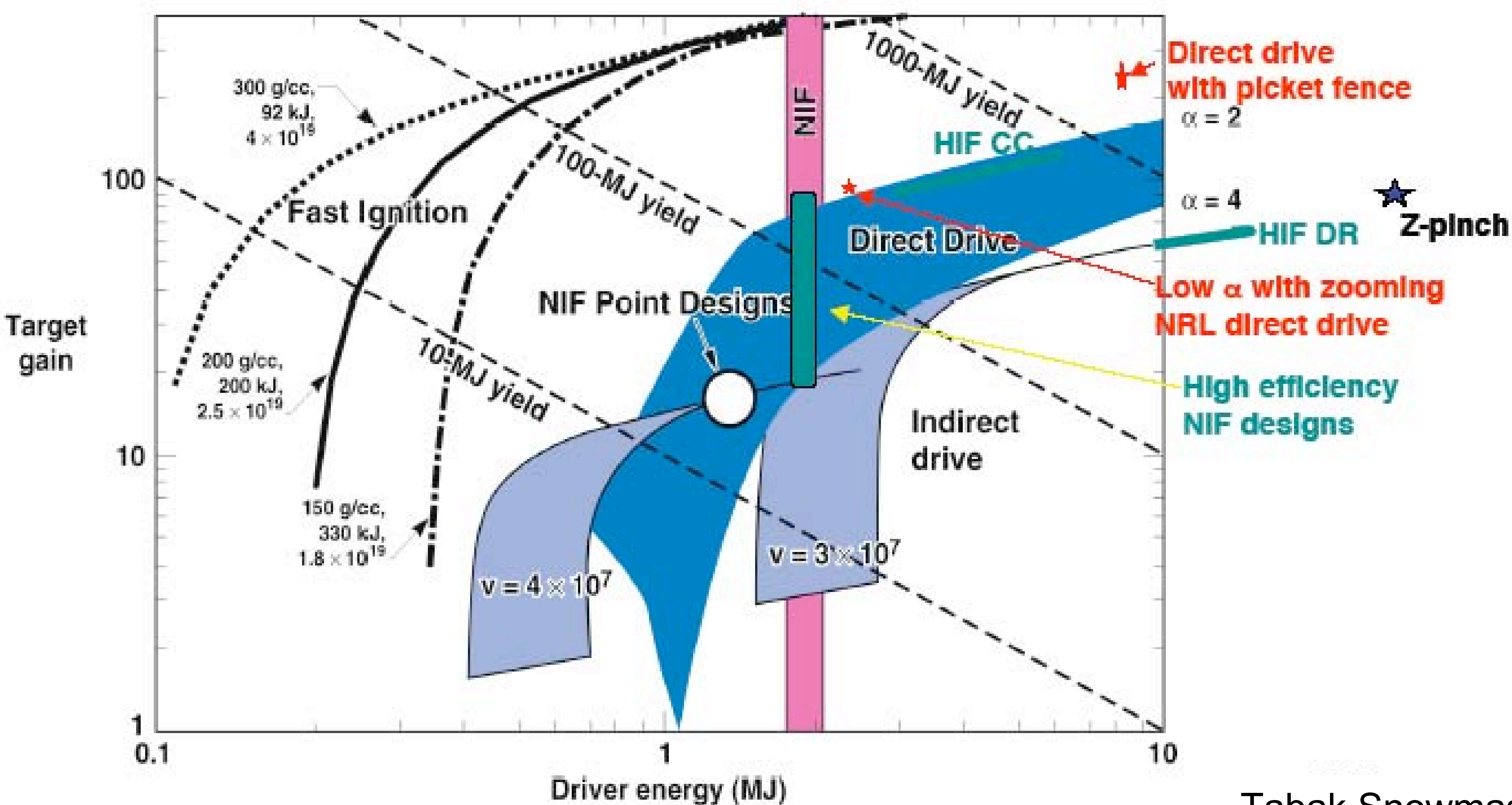
2009

1.8 MJ
351 nm

- 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



Tabak Snowmass

FI Expt's -
Omega, FIREX,
HIPER

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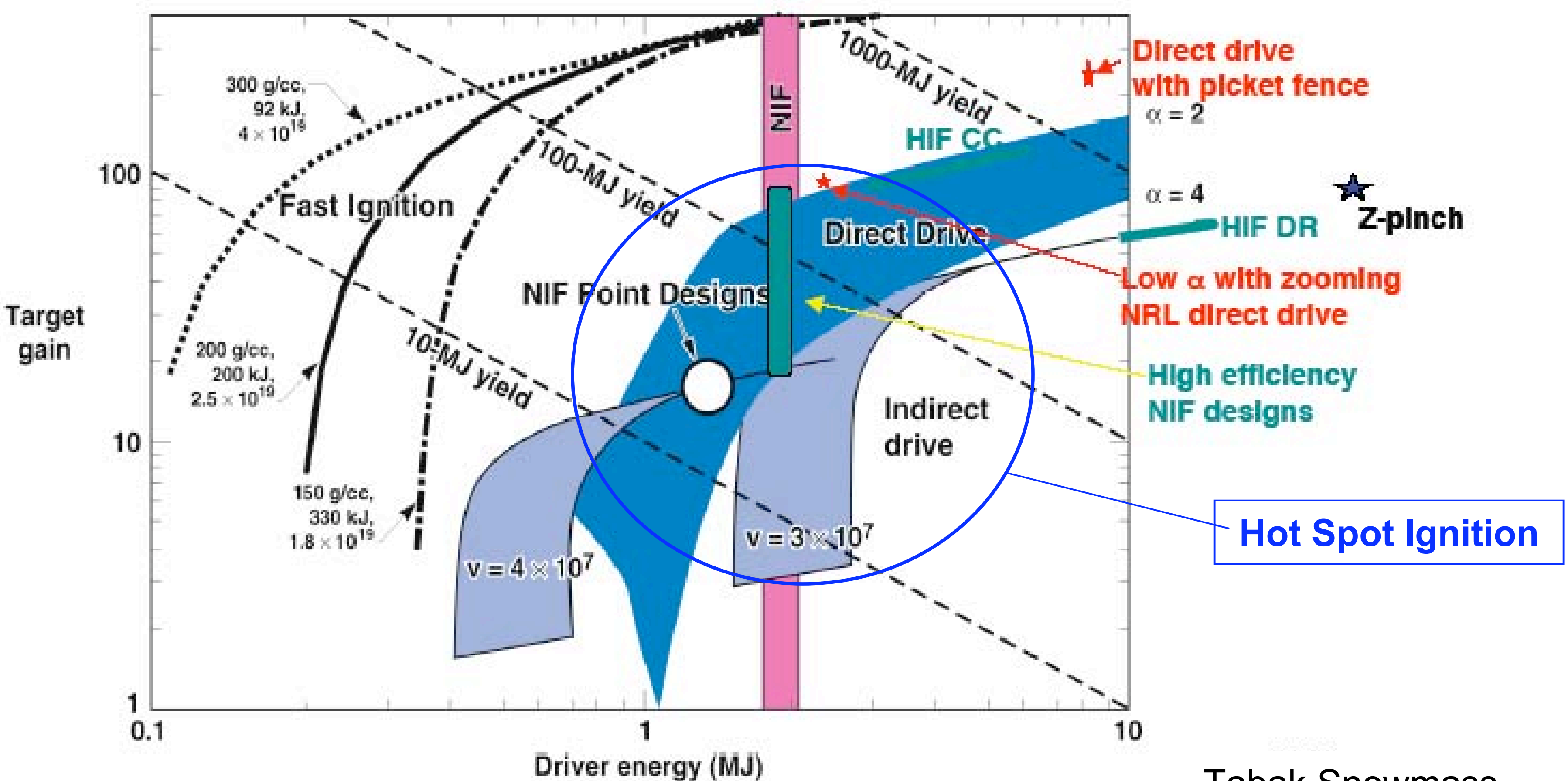

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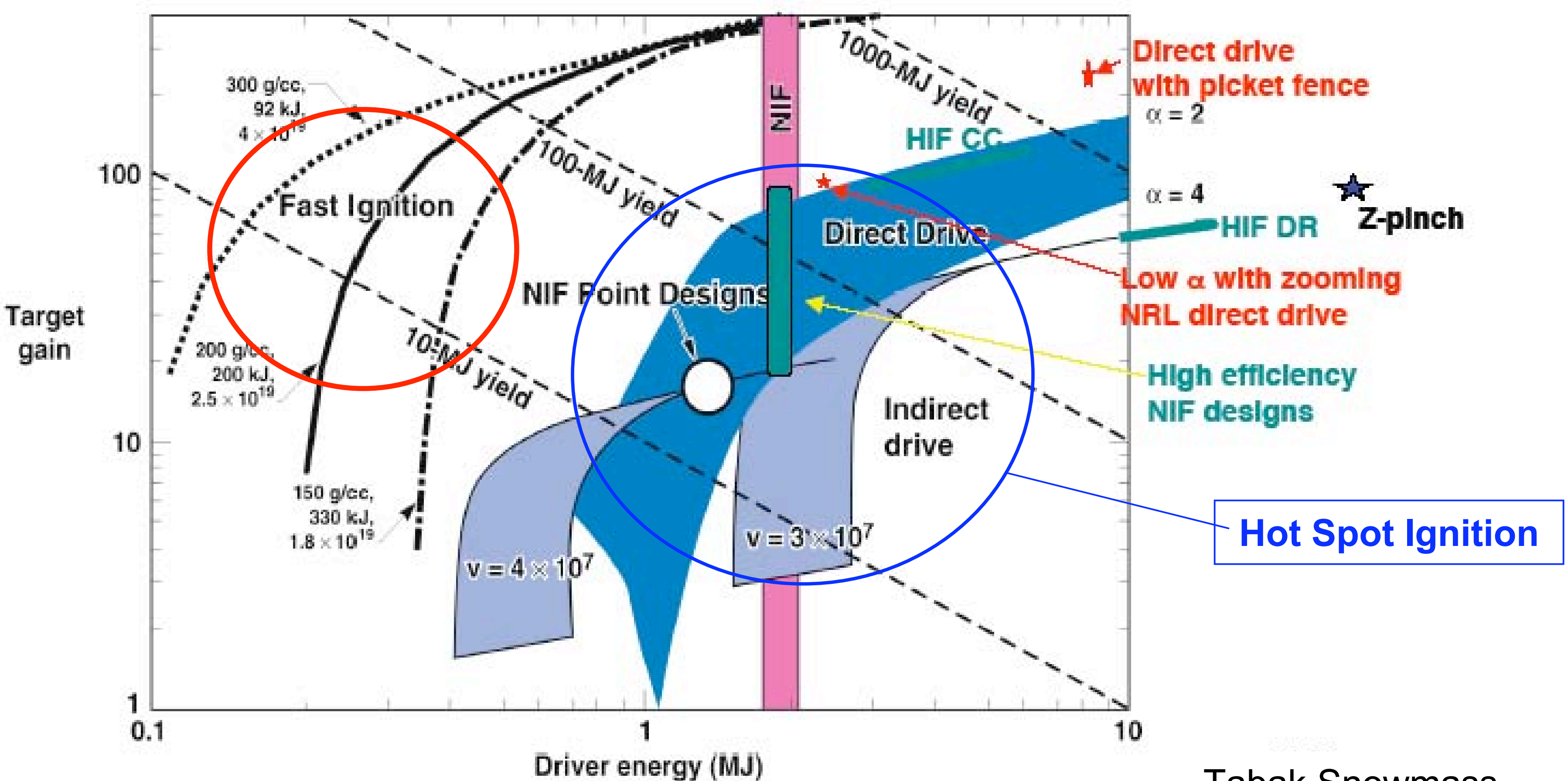


Tabak Snowmass

FI Expt's - Omega, FIREX, HIPER

NIF Ready to Begin Ignition Campaign

NIF Groundbreaking May 29, 1997

NIF Dedication May 29, 2009

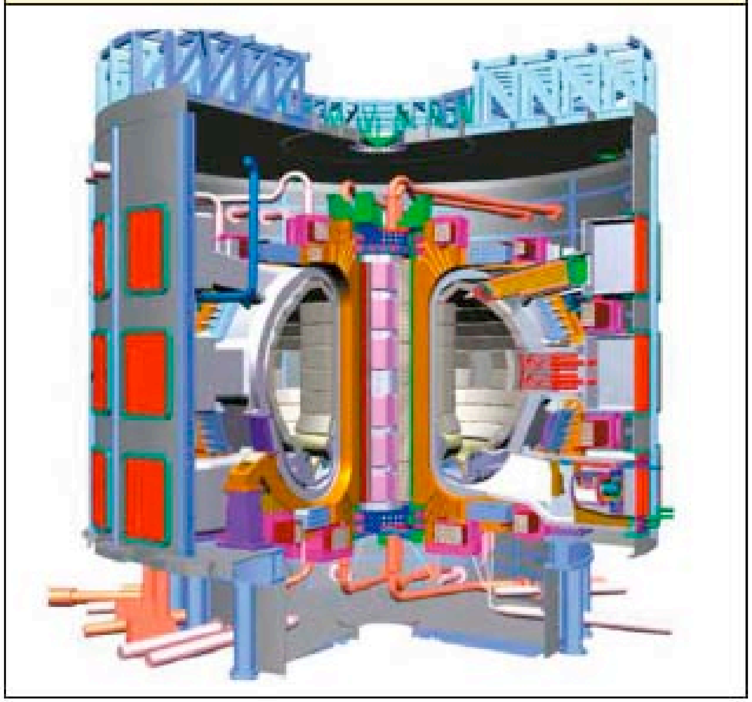
Ignition Campaign - starting 2010

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.

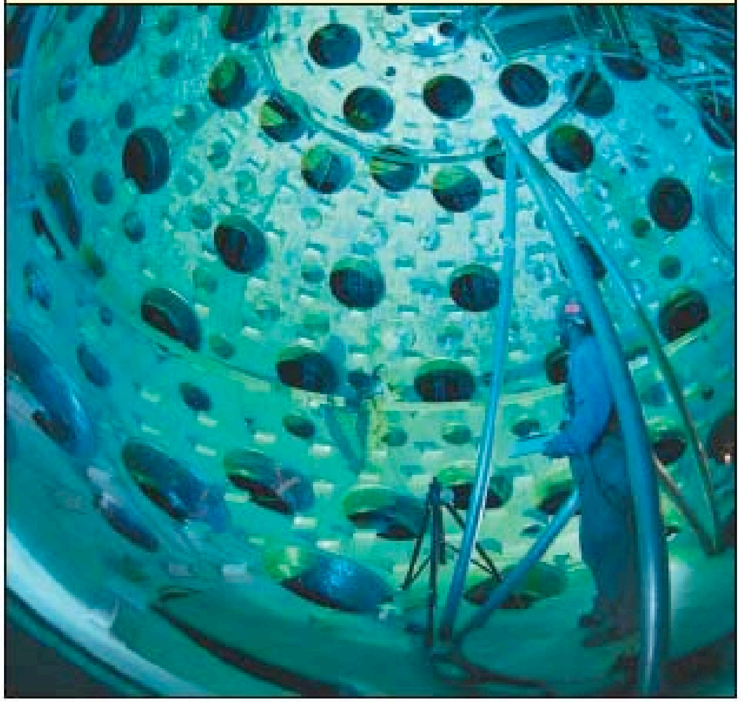
Facilities to Produce Fusion Energy are under Construction

Magnetic Fusion Energy



ITER

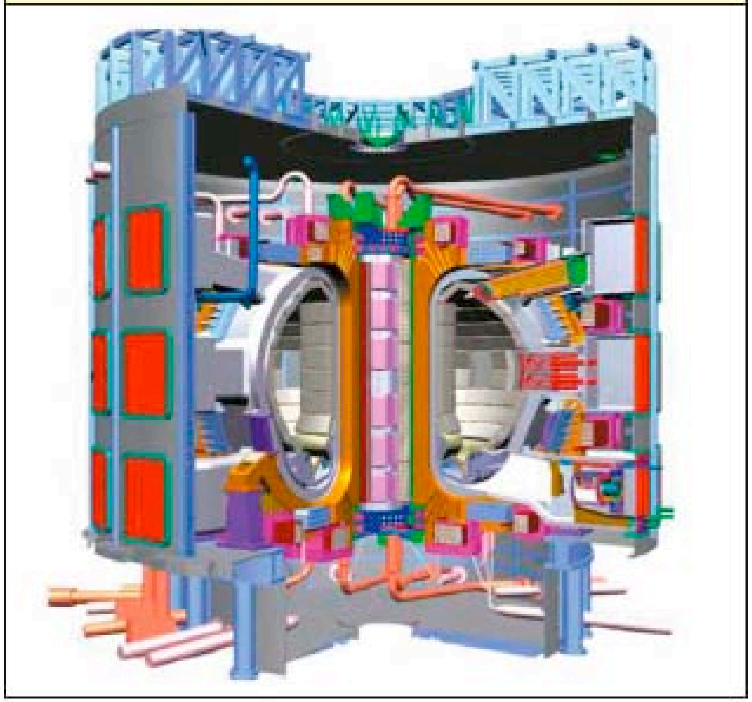
Inertial Fusion Energy

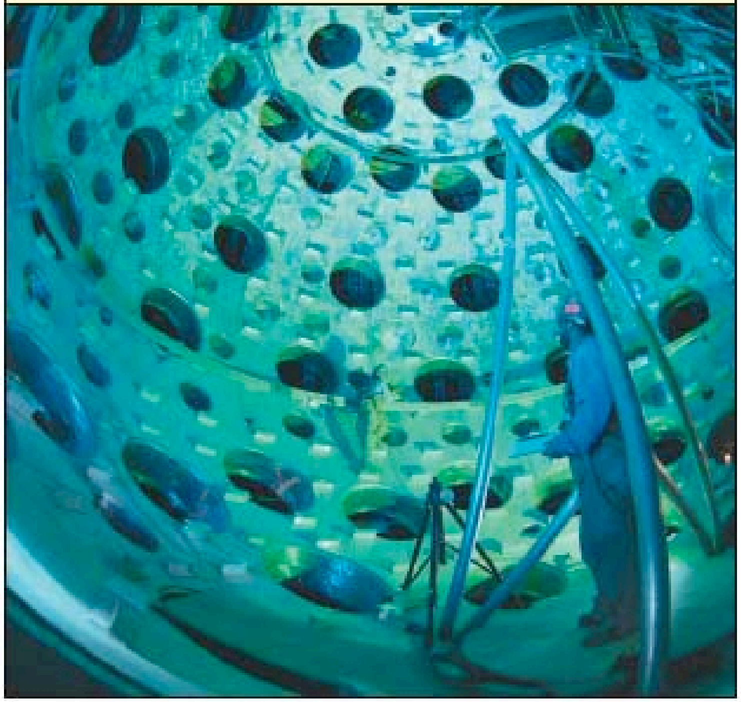


NIF

Facilities to Produce Fusion Energy are under Construction

Magnetic Fusion Energy	Inertial Fusion Energy



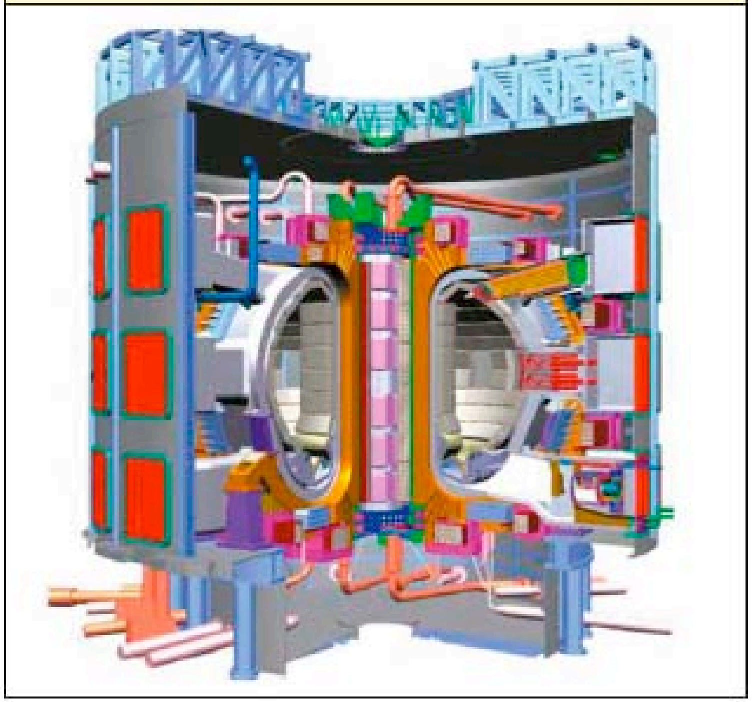
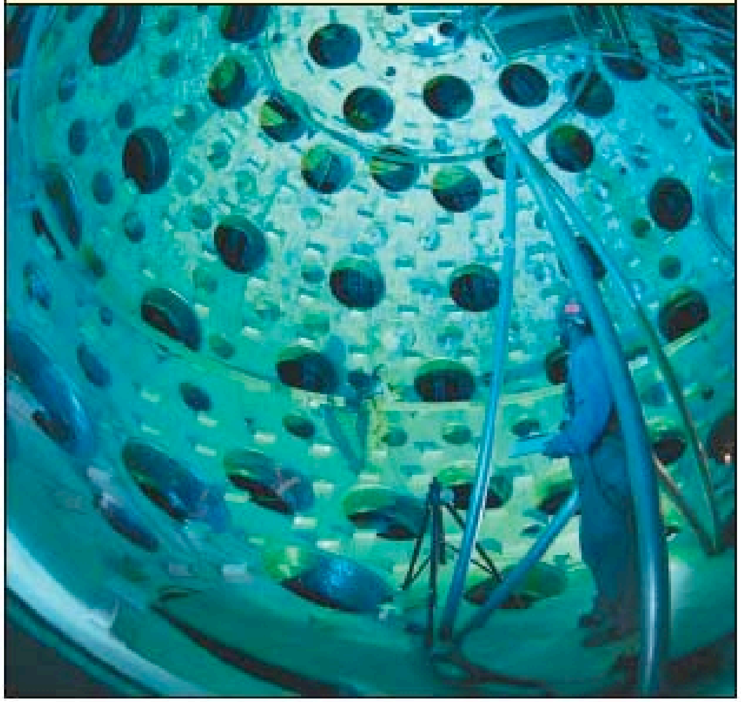


ITER

NIF

First D-T	~2010
Fusion Gain, Q	10 - 20
Fusion Energy/pulse	40 MJ

Facilities to Produce Fusion Energy are under Construction

Magnetic Fusion Energy	Inertial Fusion Energy
	

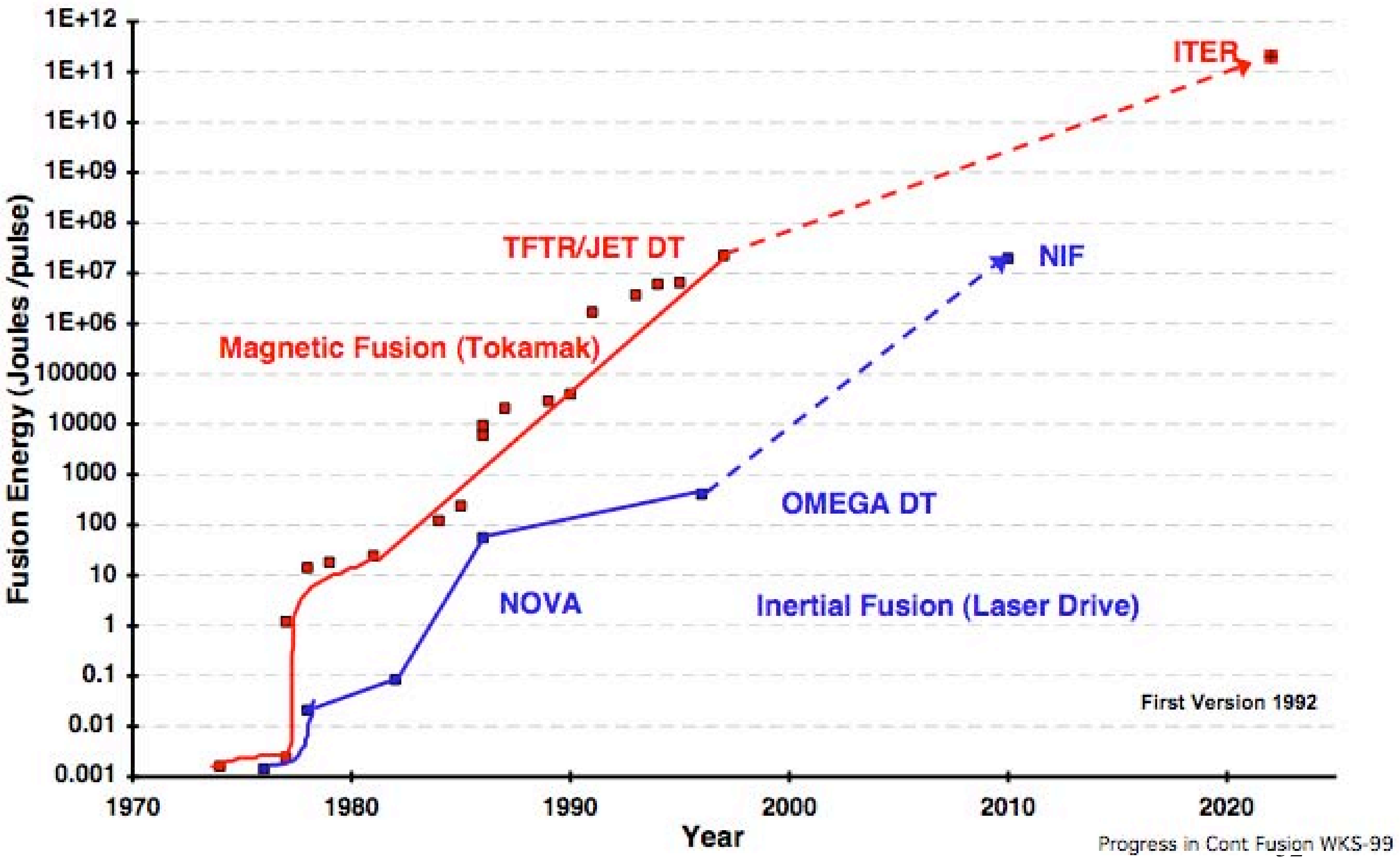
ITER

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

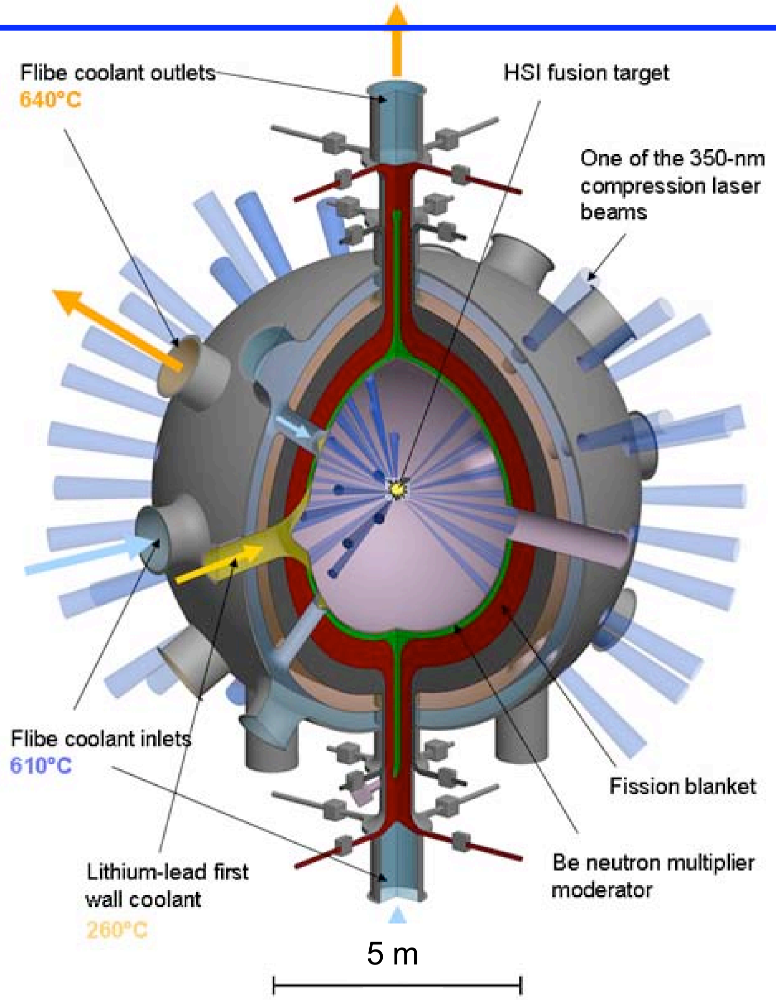
NIF

First D-T	~2010
Fusion Gain, Q	10 - 20
Fusion Energy/pulse	40 MJ

NIF and ITER will Extend Progress in Fusion Energy

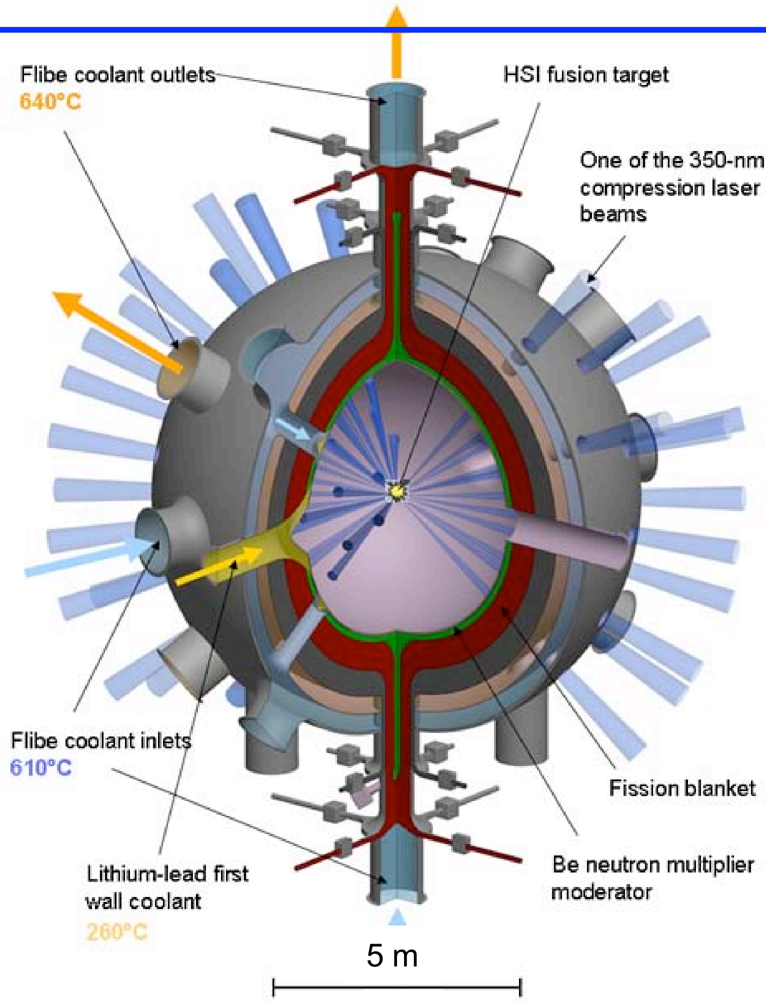


Fission-Fusion in 1 Decade



LIFE

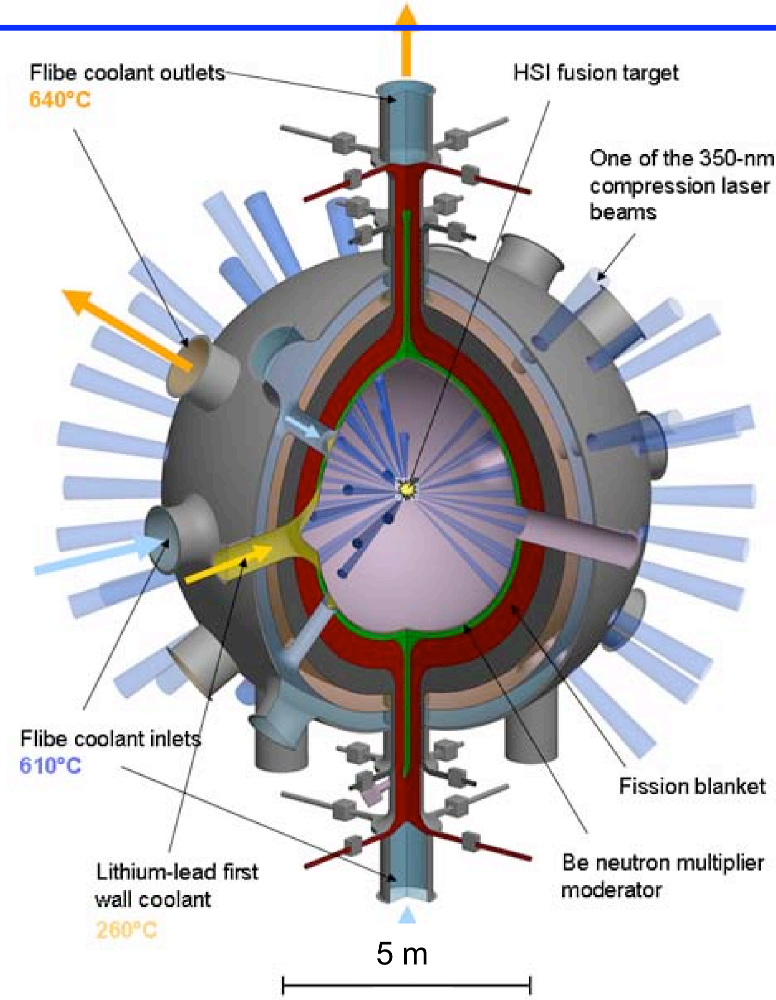
Fission-Fusion in 1 Decade

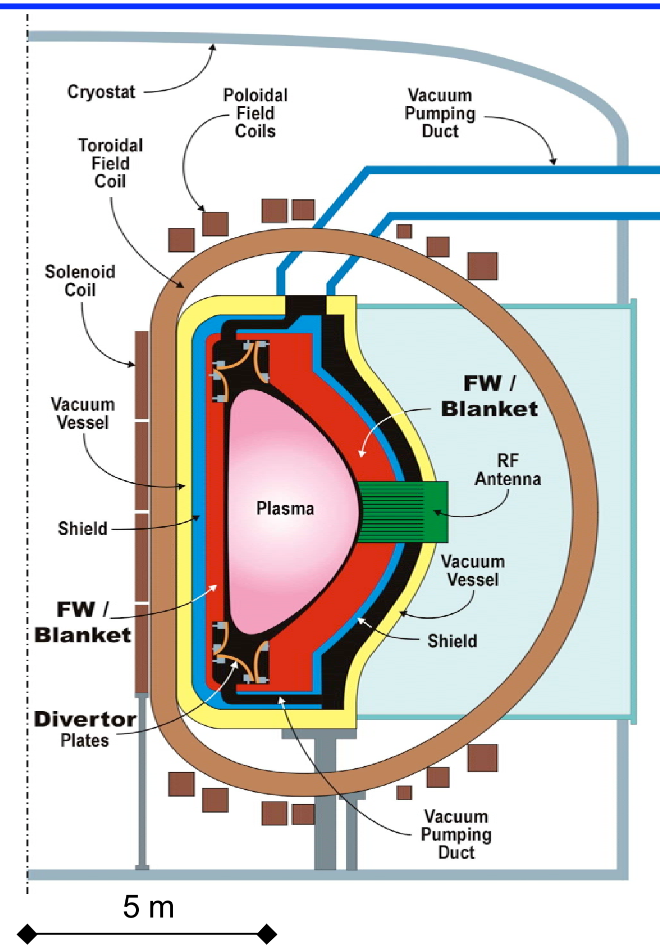


LIFE

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

Fission-Fusion in 1 Decade   Fusion in 3 Decades





LIFE   **DEMO**

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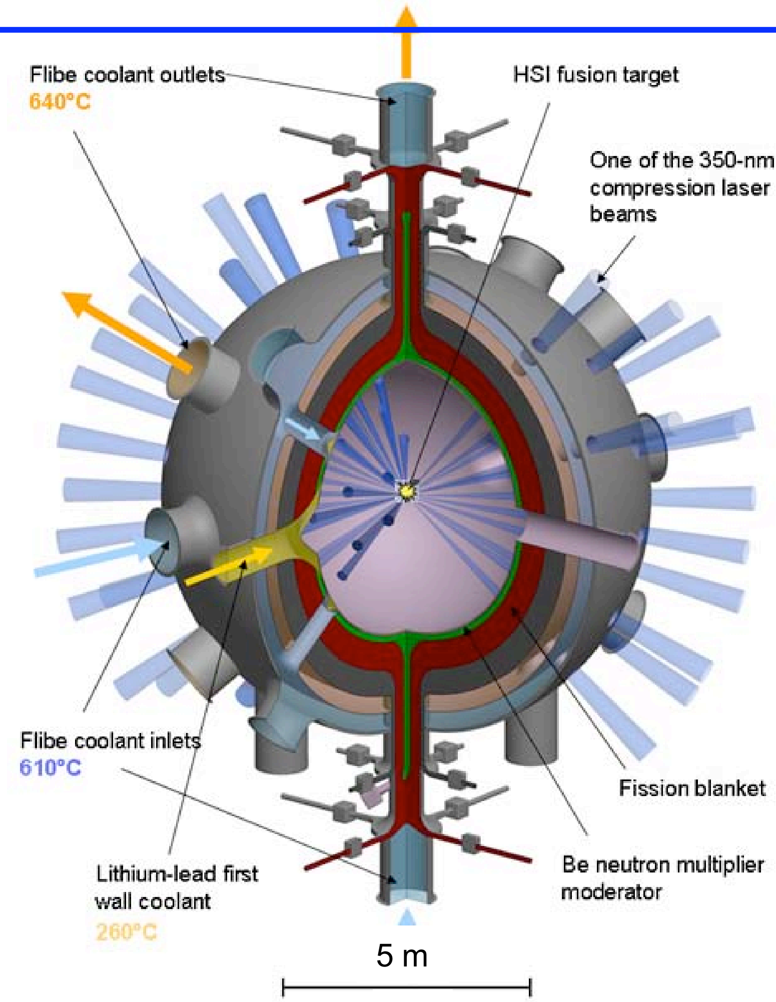
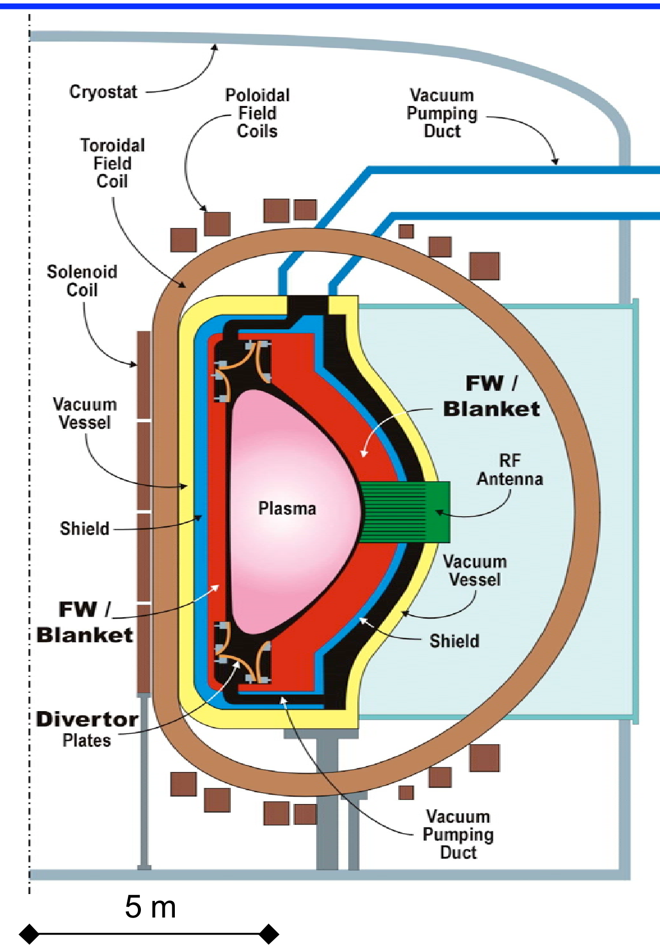
Fission-Fusion in 1 Decade



Fusion in 3 Decades



LIFE		DEMO	
First D-T	~2020	First D-T Power	~2025+15
Fusion Gain, Q	25	Fusion Gain, Q	20 - 45
Fusion Power	400 MW	Fusion Power	2,500 MW
Fission + Fusion Power	2,500 MW		

Concluding Thoughts

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- If the US had a Manhattan Project for Energy, what could fusion do?
- **A comprehensive long range plan is needed for the US magnetic fusion energy program!!**