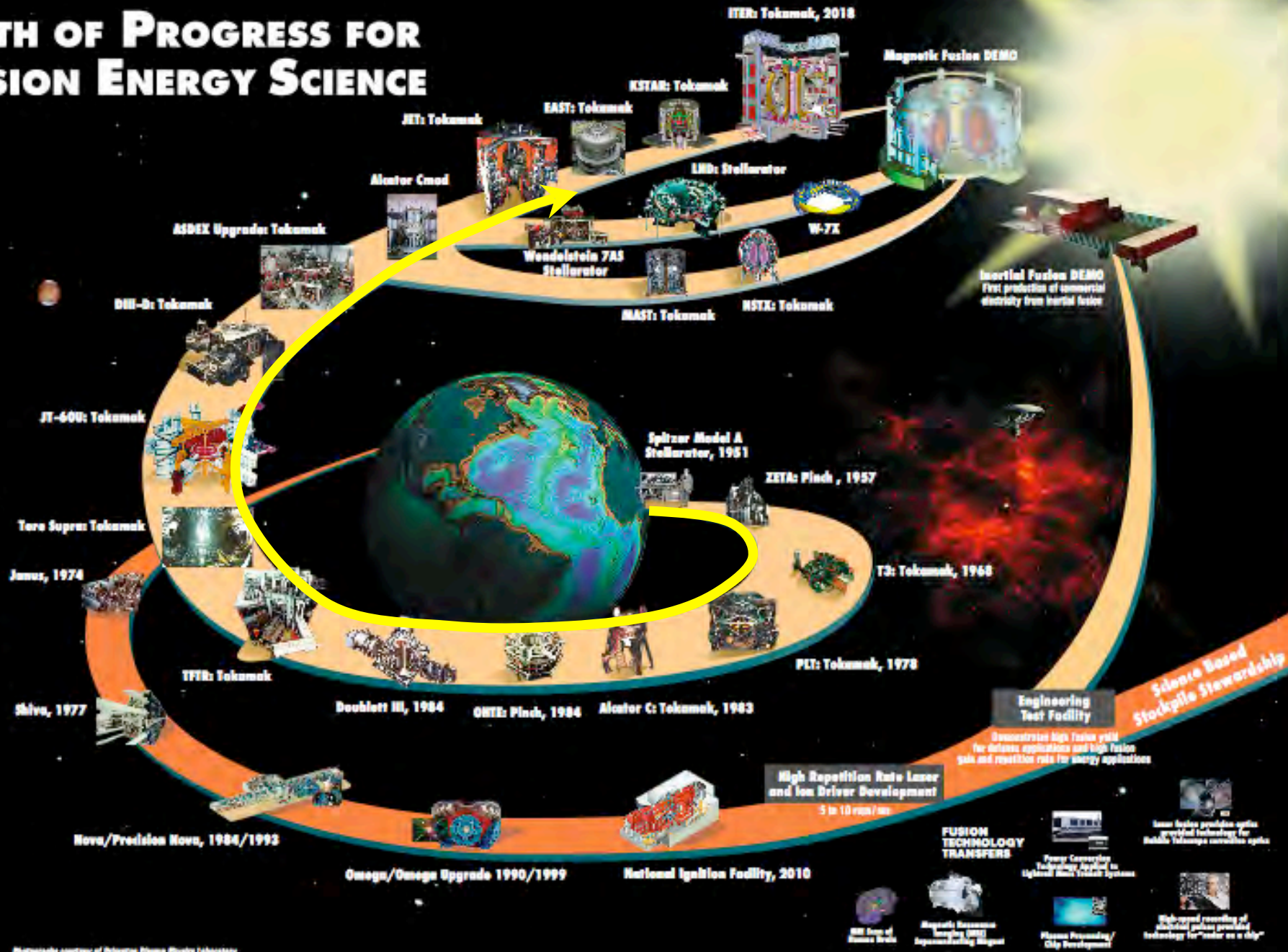


50 Years of Fusion Research

Dale Meade
Fusion Innovation Research and Energy®
Princeton, NJ

PPPL Colloquium
April 1, 2009
Princeton, NJ 08543

PATH OF PROGRESS FOR FUSION ENERGY SCIENCE



Photographs courtesy of Princeton Plasma Physics Laboratory, Lawrence Livermore National Laboratory and General Atomics



... 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
 - 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 - Tamm/Sakharov, Spitzer
- 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

Requirements for Development of Fusion

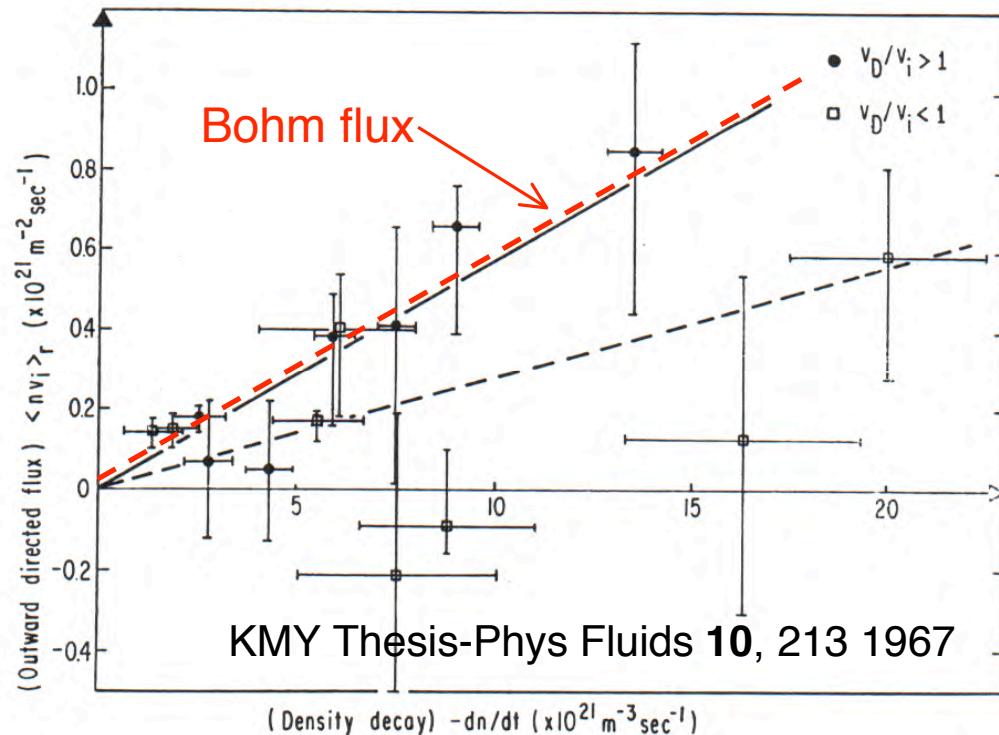
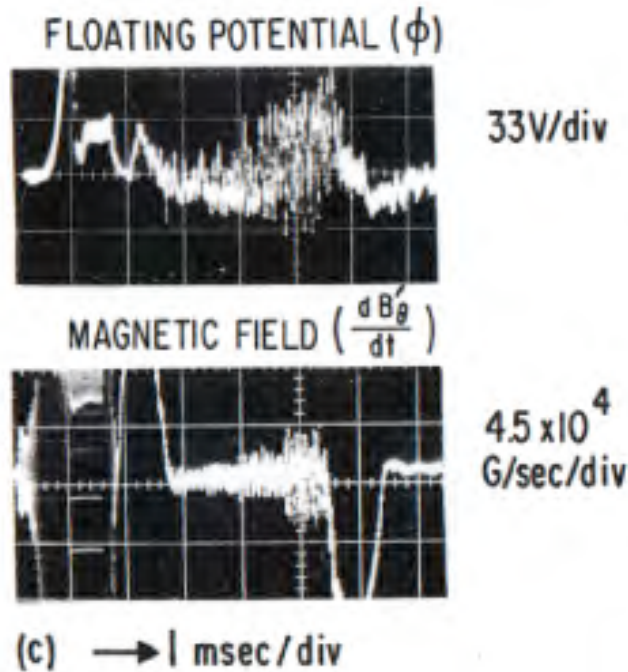
- General issues understood very early
- Reactor plasma conditions ($n\tau_E \approx 3 \times 10^{20} \text{m}^{-3}\text{s}$, $T_i \sim 20 \text{ keV}$, $Q \geq 25$)
 - confinement (turbulence), plasma heating
- Neutron Wall Loading $\sim 4 \text{ MWm}^{-2}$ (for economic attractiveness)
 - material damage $\sim 40 \text{ dpa/yr}$ with low radioactive waste
 - tritium breeding (TBR > 1) to complete the fuel cycle
- Fusion Power Densities ($\sim 5 \text{ MWm}^{-3}$, $\longrightarrow p \sim 10 \text{ atm}$)
 $\beta = \langle p \rangle / B_c^2$, MHD stability and coil engineering
- Plasma Wall Interaction -
 - $\sim 1 \text{ MW m}^{-2}$ thermal load on wall
 - low impurity levels, low tritium retention ($< 0.5 \text{ kg-T}$)
- High-duty cycle, essentially steady-state

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 \sim Bohm diffusion
 - Stabilization of interchange instability by $\text{Min}|B|$ in mirror - Ioffe
 - Stabilization of interchange in a torus by $\text{Min}\langle B \rangle$ in multipoles - Kerst/Ohkawa
 - Quiescent period in Zeta due to strong magnetic shear in self-organized state
 - Confinement gradually increased from $1 \tau_B$ to $5-10 \tau_B$ for low temp plasmas
 - Landau Damping demonstrated

The Early 1960s - The Depths of Despair for Toroidal CS

- The first stellarator experiments in the late '50s were plagued with instabilities. Stellarators were limited by fluctuations causing “pump out, Bohm Diffusion or anomalous diffusion.”
- Model C was built to reduce complications of impurities (divertor) and wall neutrals ($a = 5$ cm). Experiments in 1961-66 confirmed Bohm diffusion.



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

Increasing $B_{\text{multipole}}$

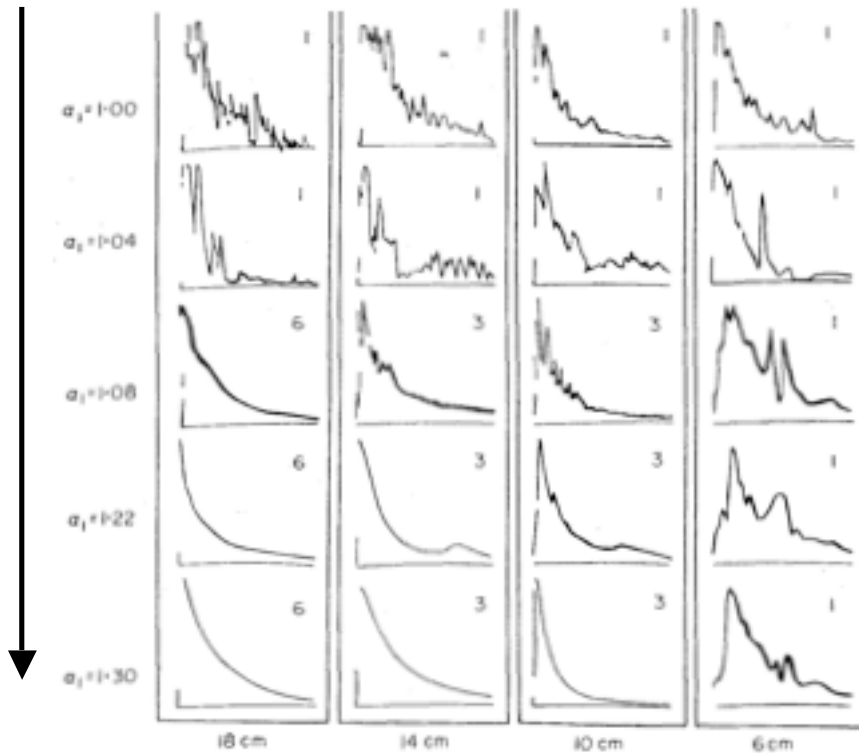
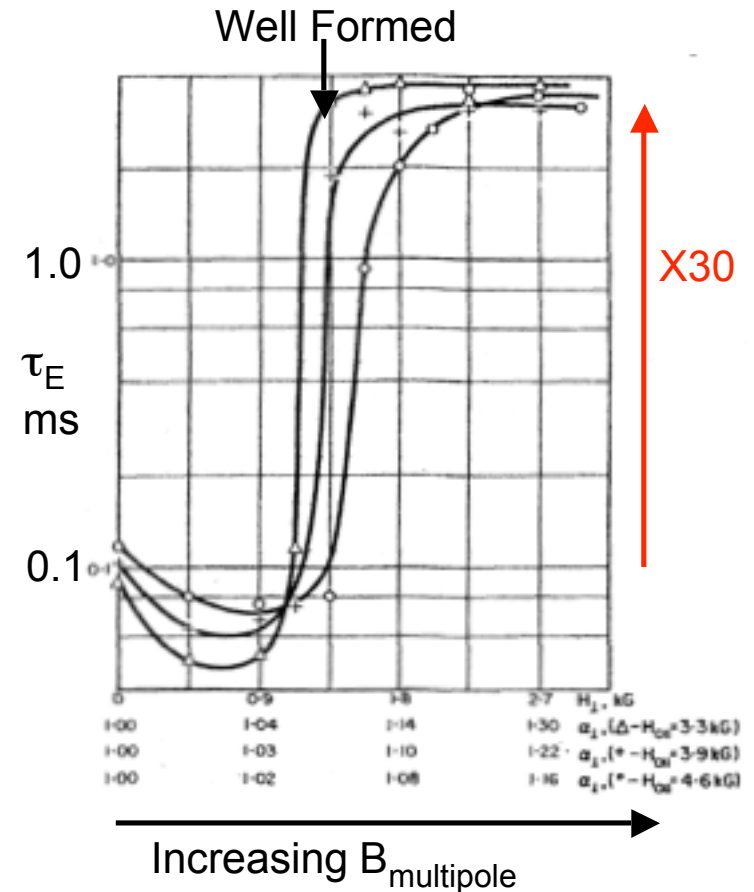


FIG. 8.—Oscillograms of ion current entering a Langmuir probe placed at various distances from the axis of the trap. (The figures in the right-hand corners of each oscillogram are the sweep lengths in milliseconds.)

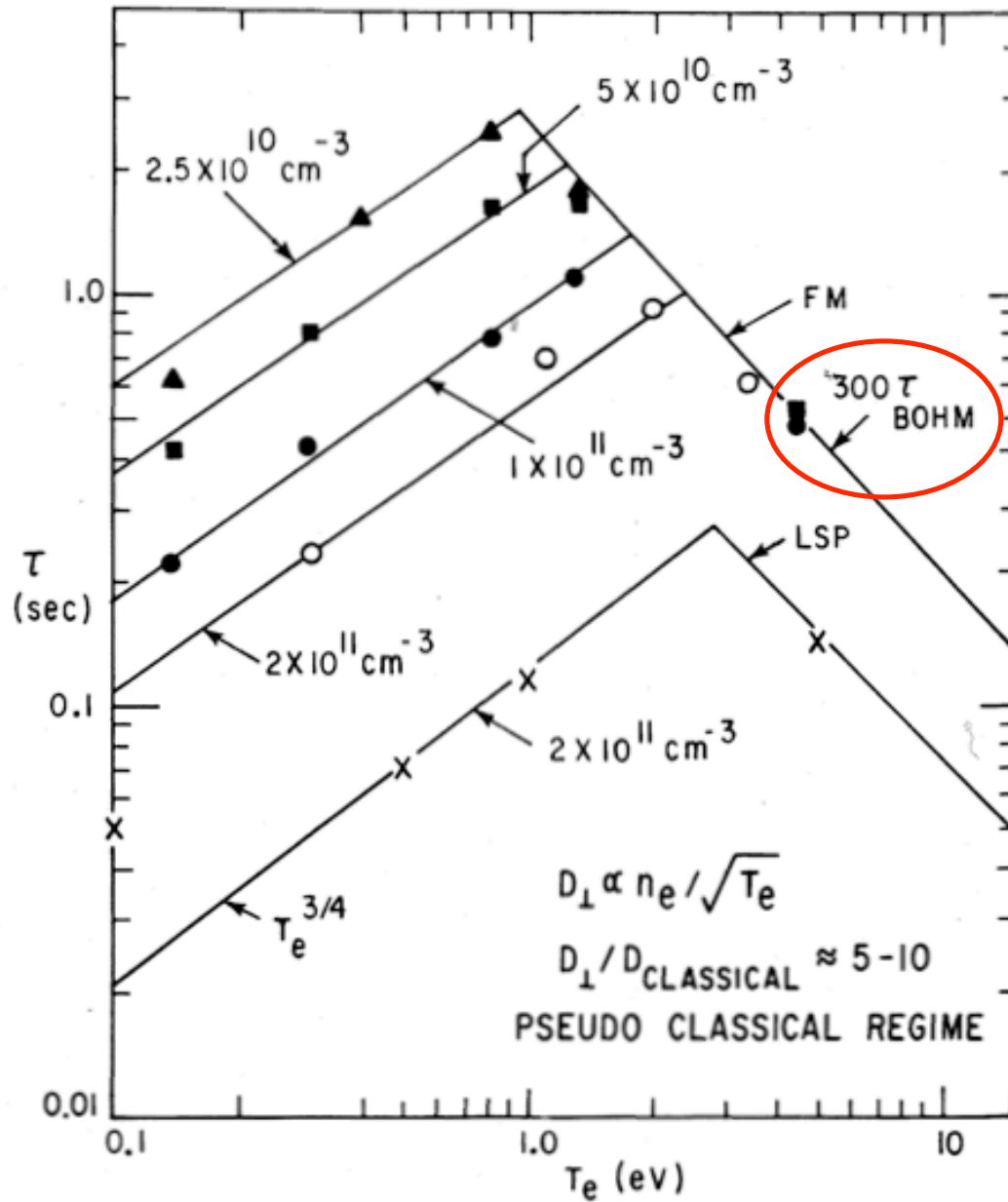


- IOFFE IAEA Salzburg 1961, J Nuc Energy Pt C 7, p 501⁷ 1965

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 - 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

Enhanced Confinement in Low Temperature Plasmas

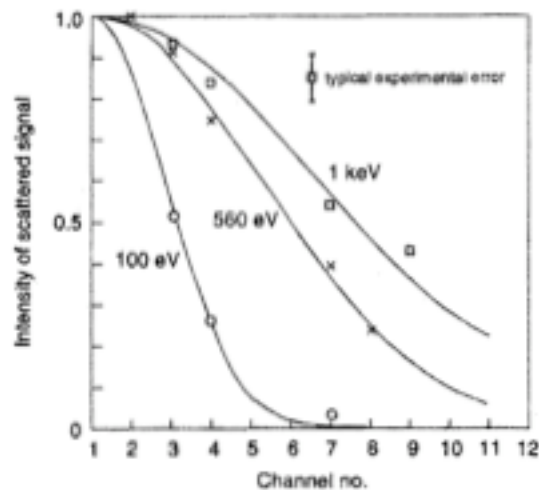


FM-1

LSP

1968-69 T-3 Breaks Bohm, Tokamaks Proliferate

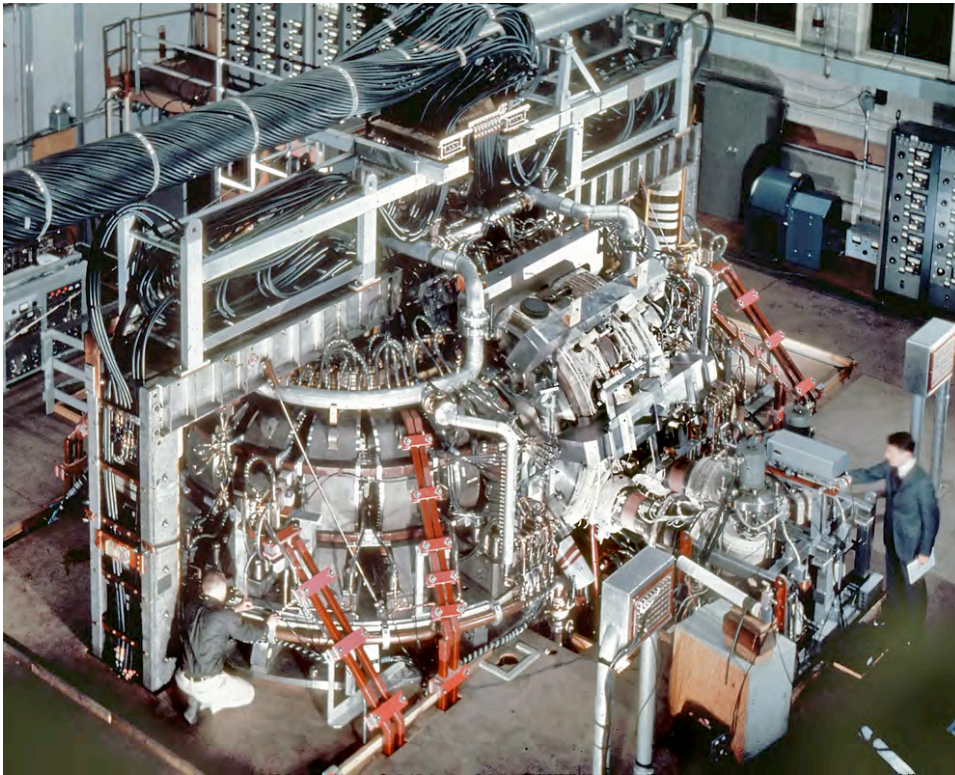
- Hints of a major advance at IAEA Novosibirsk 1968, but skeptics abound
- Thomson Scattering (Peacock/Robinson) Dubna 1969 confirms $T_e \approx 1$ keV



From Braams and Stott

- Energy confinement $\approx 30 \tau_B$ - 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.

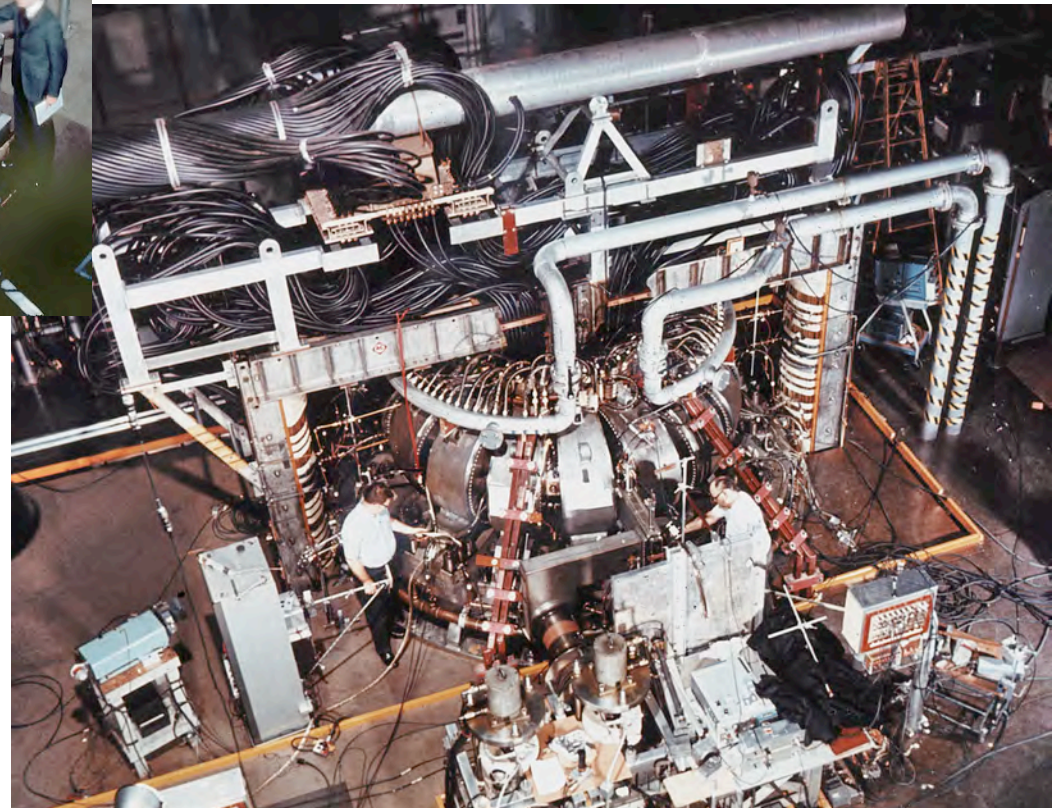
Model C Stellarator Converted to Tokamak in 6 months



Model C Stellarator
1969

T-3 results are quickly reproduced and extended.

Symmetric Tokamak (ST)
1970

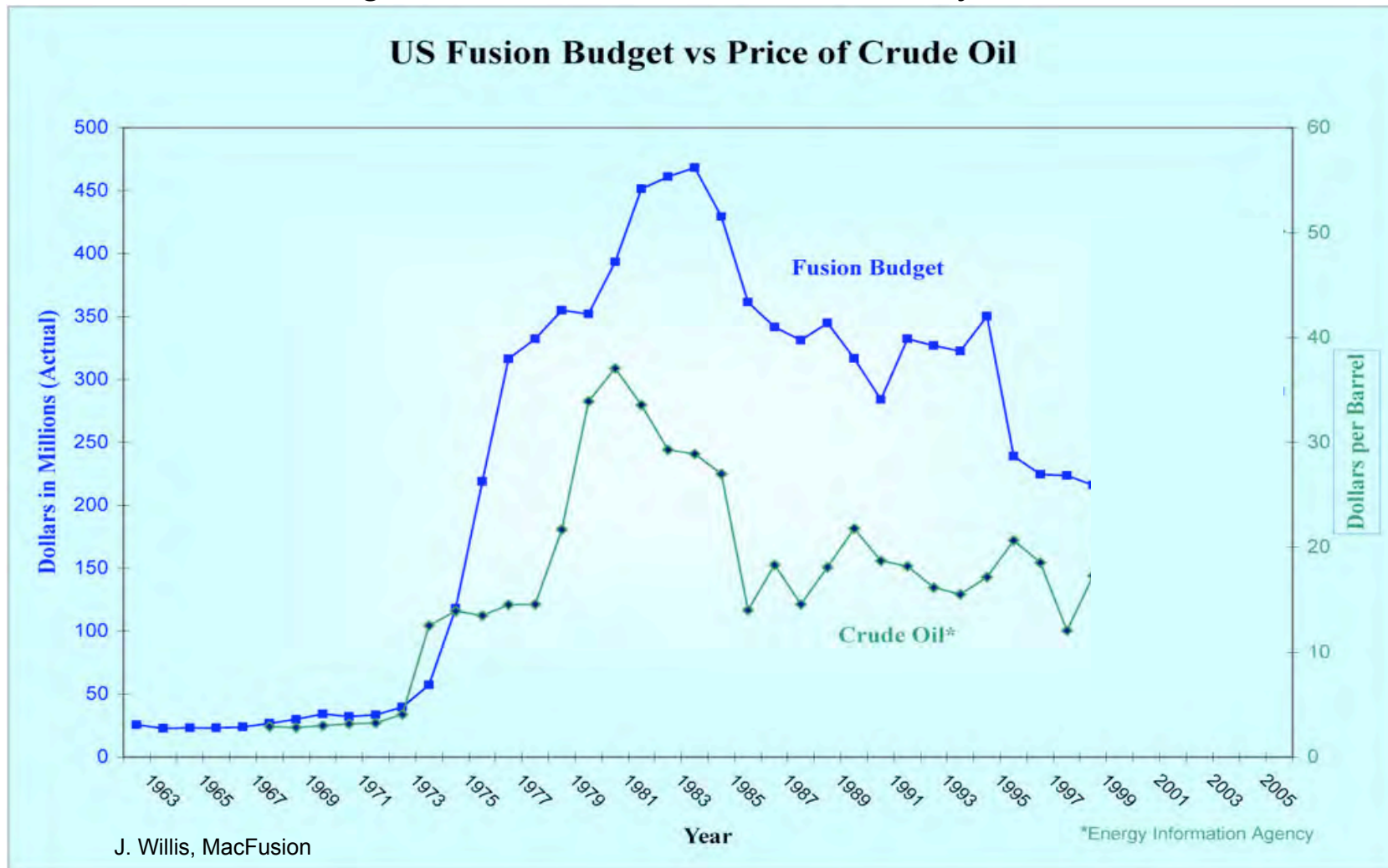


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- Energy confinement $\approx 30 \tau_B$ - Bohm barrier broken for a hot plasma
- Skeptics converted to advocates overnight, Model C Stellarator converted to Symmetric Tokamak (ST) in 6 months, T-3 results are quickly reproduced.
- • During the 1970's ~ 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 ,.....
 - 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)

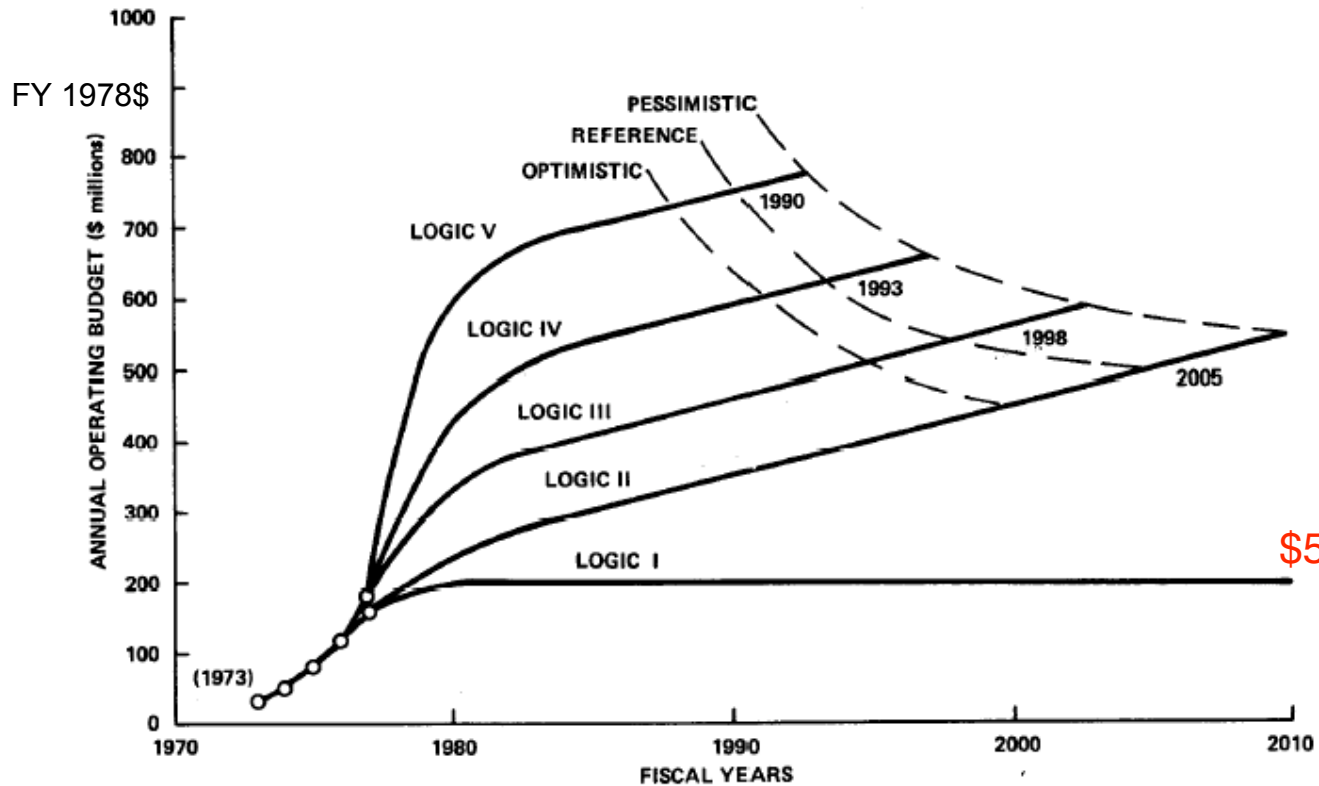
- Amid calls for increased energy R&D, Fusion budgets rise sharply
 - US Fusion budget increased a factor of 15 in 10 yrs.



1976 US Plan for Fusion

Fusion Power by Magnetic Fusion Program Plan July 1976

ERDA – 76/110/1

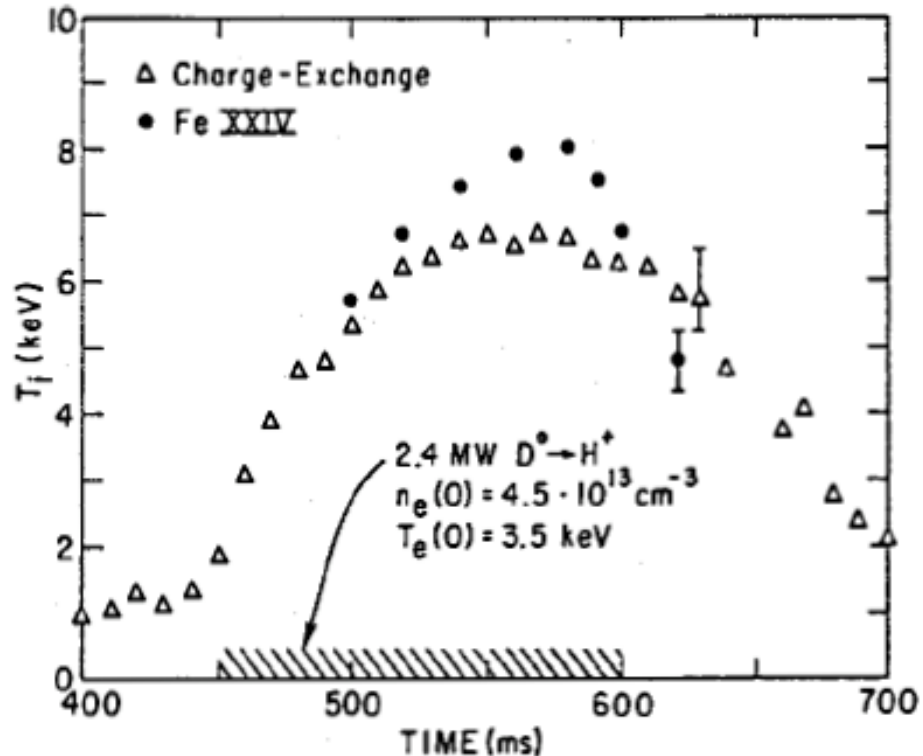


FUSION R&D PROGRAM OPERATING BUDGET AND LOCI OF DEMO OPERATING DATES FOR LOGIC I THRU V

- Logic IV became the basis for the MFE Act of 1980.

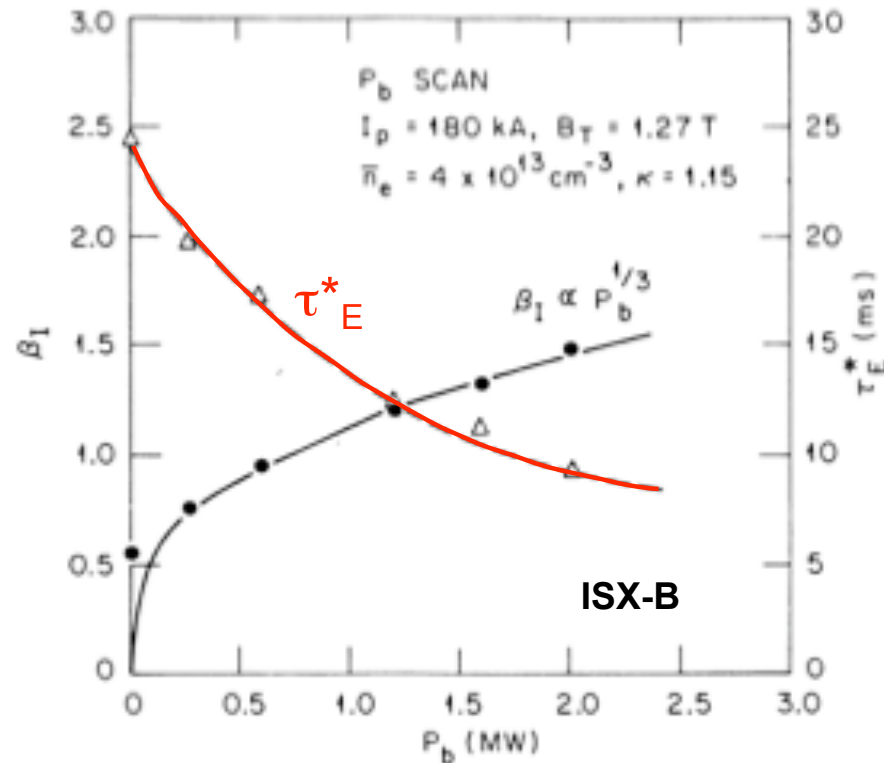
Optimism about Confinement Increased in the late 1970s

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



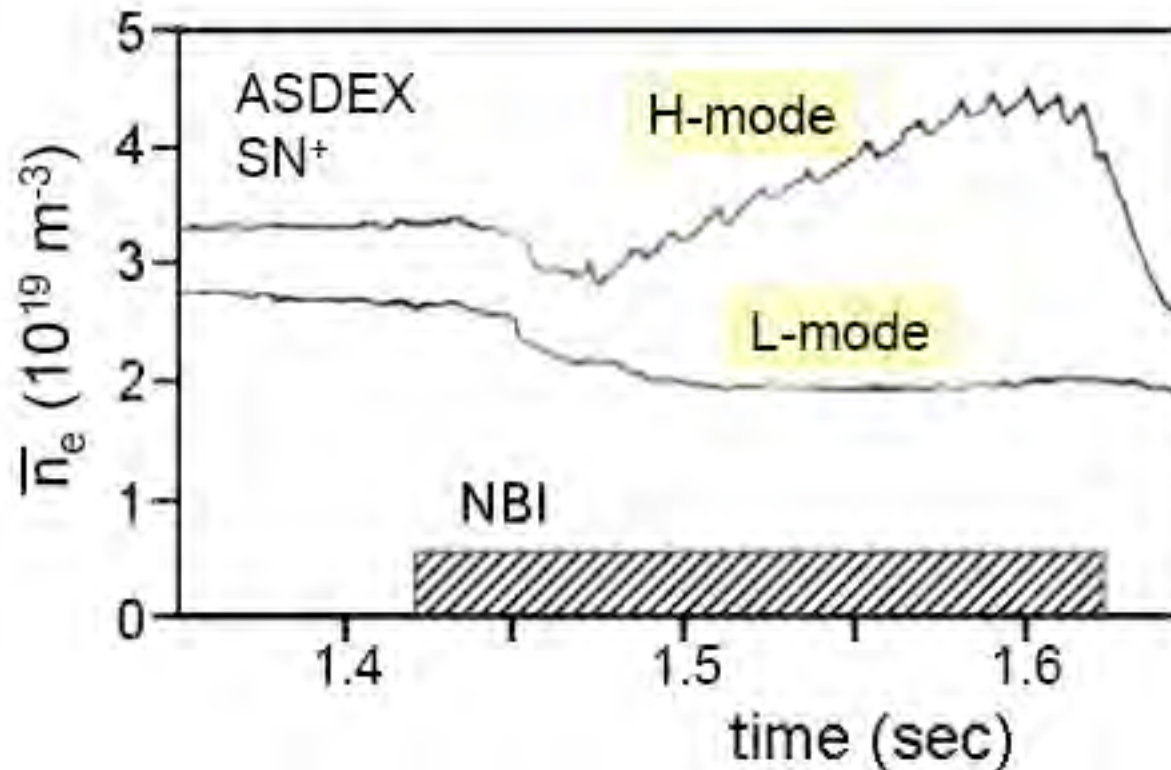
- In 1978, $T_i \sim 5.8$ keV was achieved in a collisionless plasma reducing concerns about Trapped Ion instabilities. T_i was increased to 7 keV in 1980.
- In ~ 1979 Alcator A with only ohmic heating achieved $n\tau_E \approx 1.5 \times 10^{19} \text{ m}^{-3} \text{ s}$, consistent with optimistic scaling $\tau_E \sim na^2$.

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



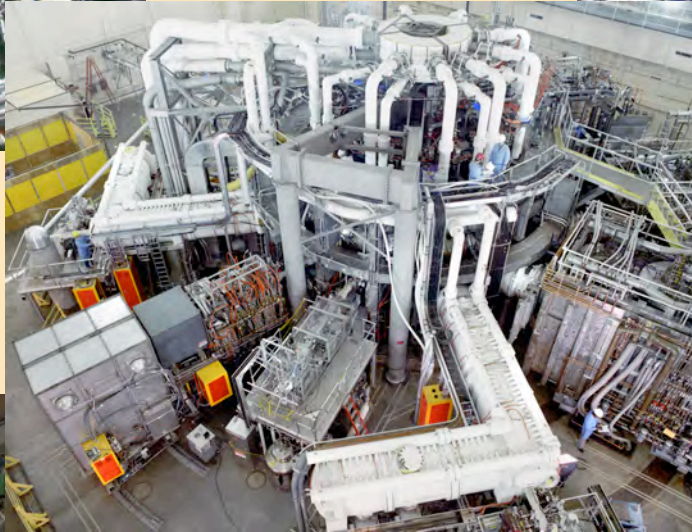
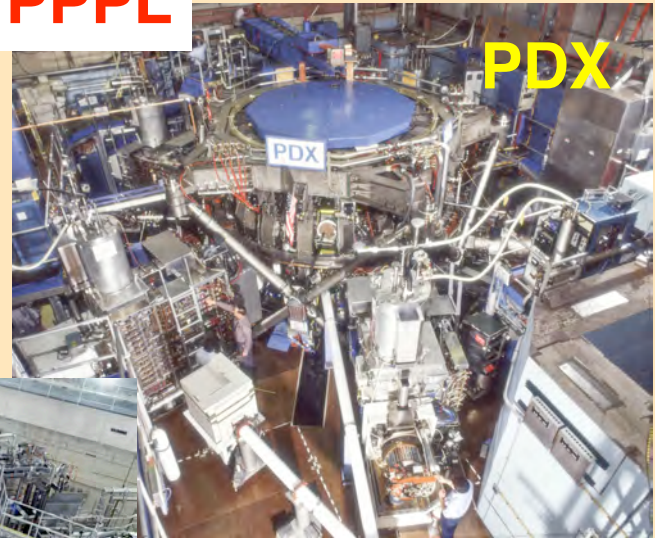
$P_{\text{NBI}} = 2.6 \text{ MW H in D}$
 $B_0 = 2.2 \text{ T}$
 $I_p = 320 \text{ kA}$
Configuration: **SN⁺**

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

The Early 1980s at PPPL



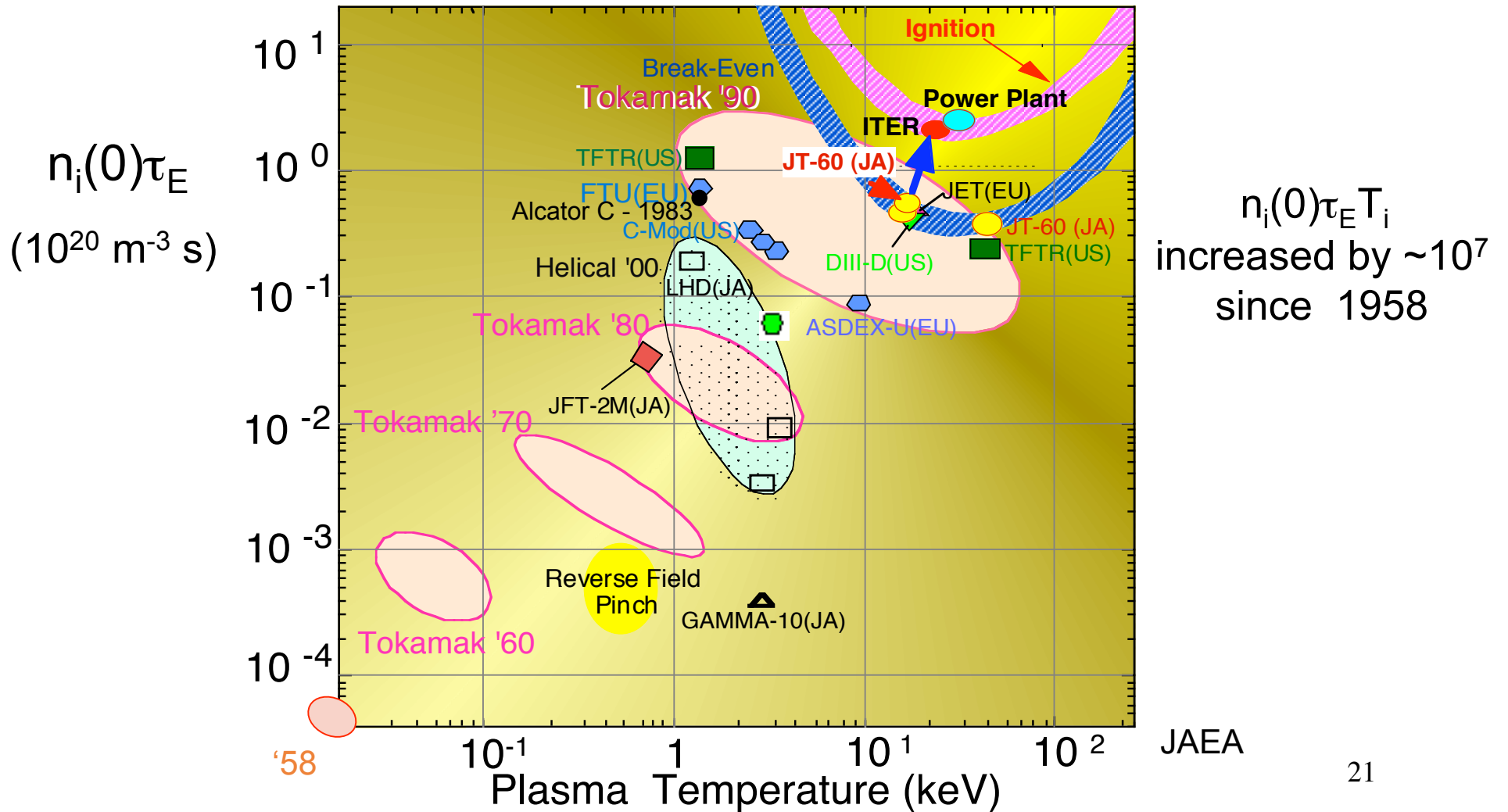
Tokamak Optimization

- 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 benefits of cross-section shaping for increased confinement and beta were demonstrated and understood in Doublet IIA and Doublet III.
 - The β limit formulation by Troyon and Sykes provided a design guide for β .
 - Empirical scaling formulations (e.g., Goldston scaling) provided guidance for τ_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 tokamaks.

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
 - $T_i \sim 20$ keV and $n_e(0)\tau_E \sim 1.5 \times 10^{19} \text{ m}^{-3} \text{ s}$ with neutral beam injection
 - $n_e(0)\tau_E \sim 1.5 \times 10^{20} \text{ m}^{-3} \text{ s}$ 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, pellet injection, PFCs

Fusion Temperatures Attained, Fusion Confinement One Step Away



Significant Fusion Power (>10MW) Produced 1990s

- **1991 JET 90/10-DT, 2 MJ/pulse, $Q \sim 0.15$, 2 pulses**
- **1993-97 TFTR 50/50-DT, 7.5MJ/pulse, 11 MW, $Q \sim 0.3$, 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 $\Rightarrow Q_{DTequiv}$ in JT-60U DD using AT mode 1996
 - Bootstrap and current drive extended
- **1997 JET 50/50-DT 22MJ/pulse, 16 MW, $Q \sim 0.65$, ~100 D-T pulses**
 - Alpha heating extended, ICRF DT Scenarios extended,
 - DT pulse length extended
 - Near ITER scale D-T processing plant
 - Remote handling

TFTR Fusion Achievements (1)

Official Objectives (1976):

1. Study plasma physics of large tokamaks,
2. Gain experience with reactor scale engineering,
3. Demonstrate D-T fusion energy production (1 to 10 MJ per pulse),

- First magnetic fusion experiment to achieve power plant fuel temperature of 200 million °C (20 keV) (1986), and ultimately a record 510 million °C (45 keV) (1995)
- Record Lawson $n\tau_E \approx 1.5 \times 10^{20} \text{ m}^{-3} \text{ s}$ at 1.5 keV using pellet injection in deuterium plasmas
- First magnetic fusion experiment to use fusion power plant fuel mixture of 50% deuterium (D) and 50% tritium (T) (1993)
- First magnetic fusion experiment to produce fusion power exceeding 10 million watts (1994)
- Fusion Power Gain ~ 0.3 , and factor of 10^6 greater than achieved when TFTR design started. the public goal was breakeven or $Q \sim 1$.
- Record peak plasma pressure of 6 atm in a D-T plasma, higher than that expected in ITER. (1994)
- Record fusion power densities of 0.3 million watts per cubic meter comparable to the 0.5 MWm^{-3} expected in ITER (1994)

TFTR Physics Achievements (2)

- First direct measurements of long wavelength turbulence that formed the basis for an improved theoretical modeling of turbulence (1990)
- First observation of the "bootstrap current" in a tokamak, a self generated current that is the key feature of steady-state tokamak fusion power plants (1986)
- First experimental observation of the "enhanced reversed shear" confinement mode that is now a key feature of steady-state tokamak power plant concepts. (1994)
- First demonstration of radio frequency heating of a D-T plasma using second harmonic tritium resonance, 1994.
- First demonstration of mode conversion heating in a D-T plasma, 1995.
- First observation of neoclassical tearing modes that limit output of high performance fusion plasmas (1995)
- First unambiguous measurements of self-heating by alpha particles in a DT fusion plasma (1995)
- First measurements of instabilities excited by fusion alpha particles (1996).

TFTR Engineering Achievements (3)

- First to identify and quantify the retention of tritium in graphite plasma facing components as a major issue for fusion power plants using trace tritium (1989) and 50/50 DT (1995)
- First closed cycle processing of tritium on a fusion experiment using 50% deuterium (D) and 50% tritium (T) (Feb 1997)
- About 1 million curies of tritium was handled safely over a three year period during over 1,000 DT experiments.
- TFTR engineering systems operated above the original design ratings for toroidal field and neutral beam power.
- The total cost of the TFTR program (design, construction, operation and decommissioning) was \$1.65 B, or 22% of the the US fusion program from 1975 to 1997.

The Next Step Burning Plasmas

- 1980 - Fusion Engineering Device (FED), SC or Cu coils, 200 MW, 200s as part of MFE Act to be completed 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

	<u>TOKAMAK</u>	<u>POWER SUPPLIES</u>
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 @ $\alpha = 3.1$	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

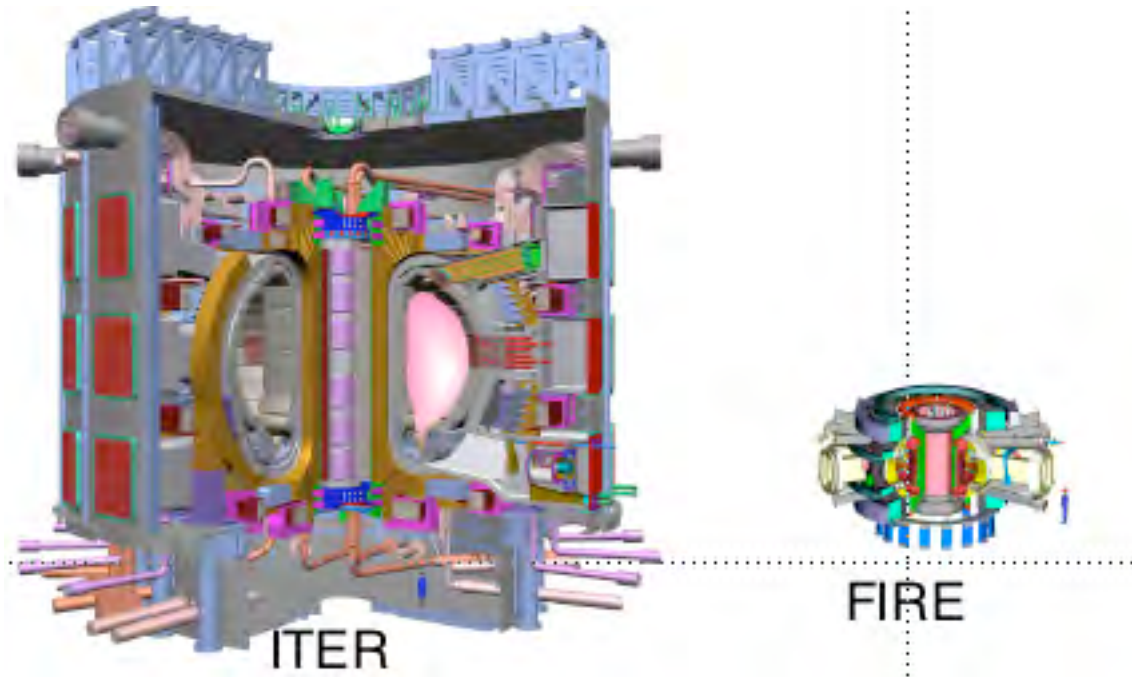
*A LIMITED NUMBER OF 11 T DISCHARGES IS ALSO AVAILABLE.

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

Burning Plasmas in the 21st Century

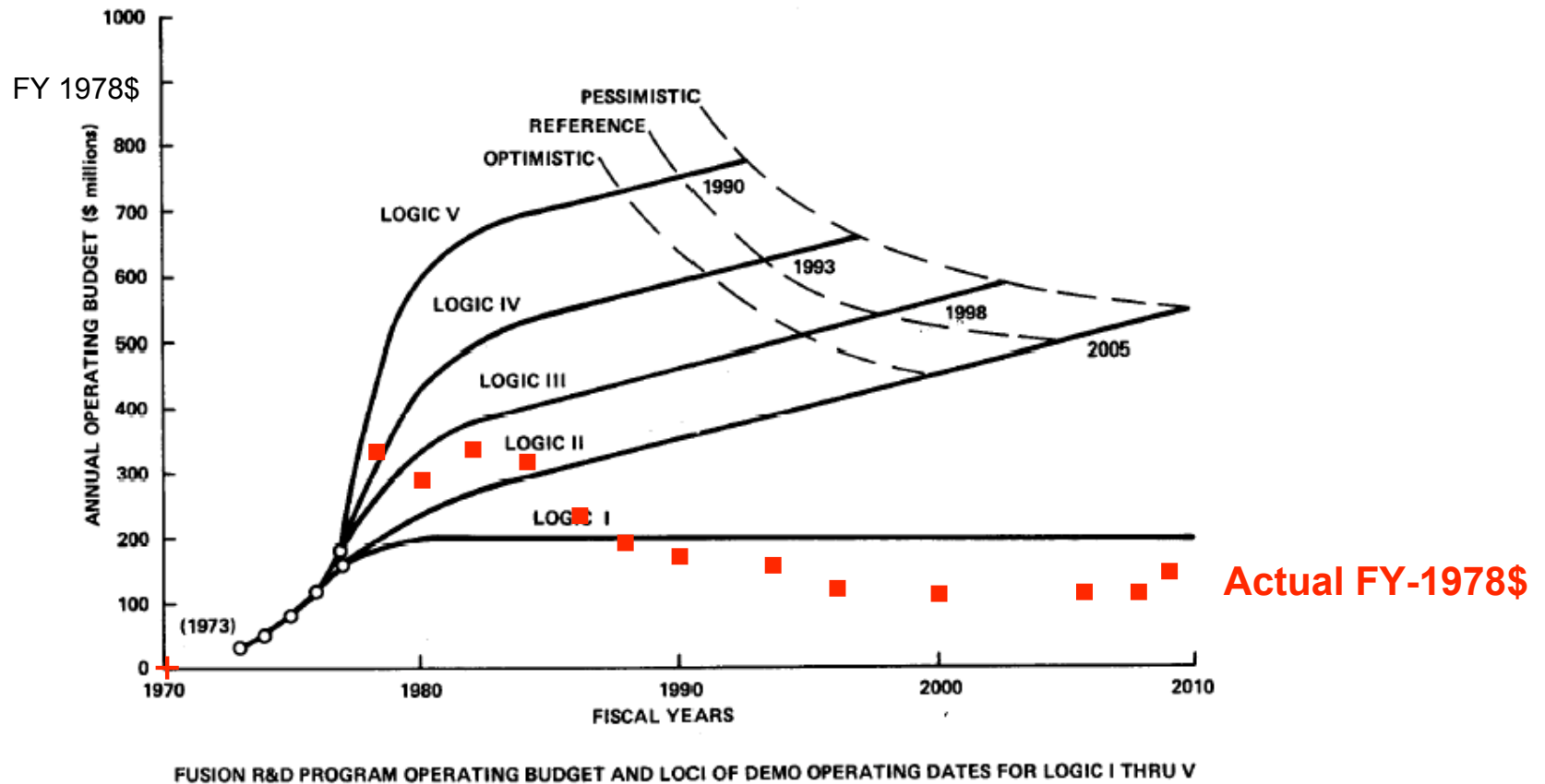


Snowmass 2002 - assessment of ITER , FIRE and Ignitor

- ITER/FIRE - similar H-Mode and AT physics capability
- ITER design complete with >80 procurement packages ready to go to industry
- ITER total cost estimate = \$5B,
US cost (10%) = \$0.5B
- FIRE total cost estimate = \$1.2B
US Cost (100%) = \$1.2B

Why Couldn't US MFE Take the Next Step?

Fusion Power by Magnetic Fusion Program Plan July 1976 ERDA – 76/110/1



- Logic IV became the basis for the MFE Act of 1980.
- The US Fusion Program evolved on to Logic I - we never get there.

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

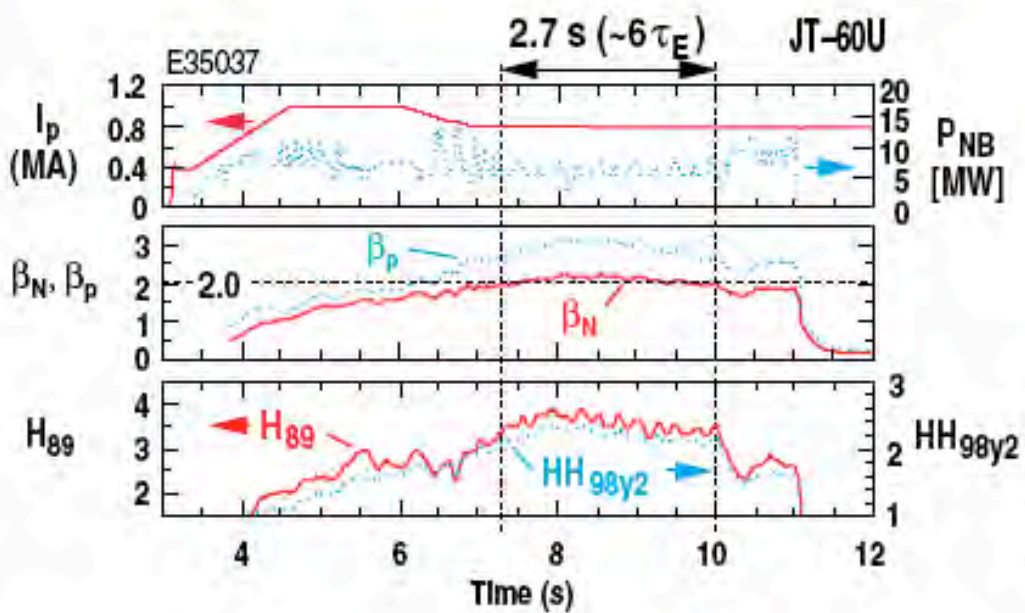
- Plasma cross-section shaping to enhance plasma current, power production
 - 1968 Ohkawa (Plasma Current Multipole), 1973 T-9 Finger Ring,



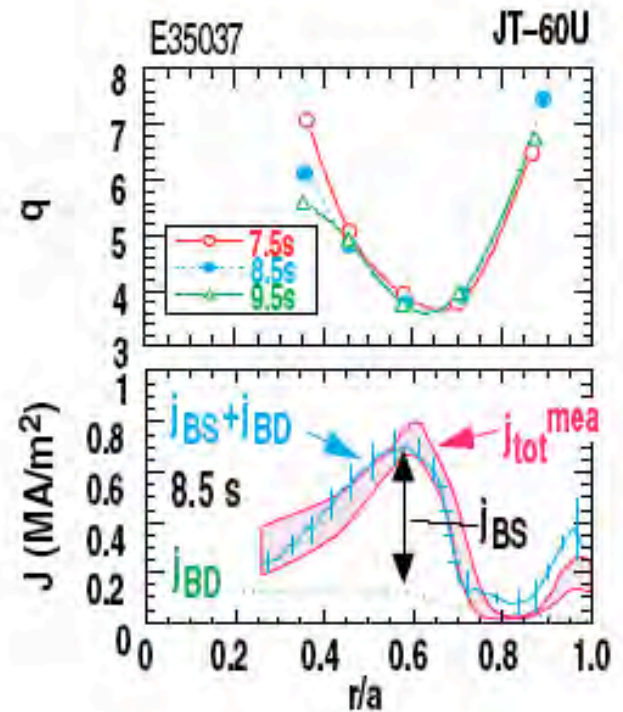
Tihiro Ohkawa with toroidal multipole at GA 1966

A HIGH PERFORMANCE PLASMA WITH FULL NON-INDUCTIVE CURRENT DRIVE AND 80% BOOTSTRAP FRACTION IN JT-60U

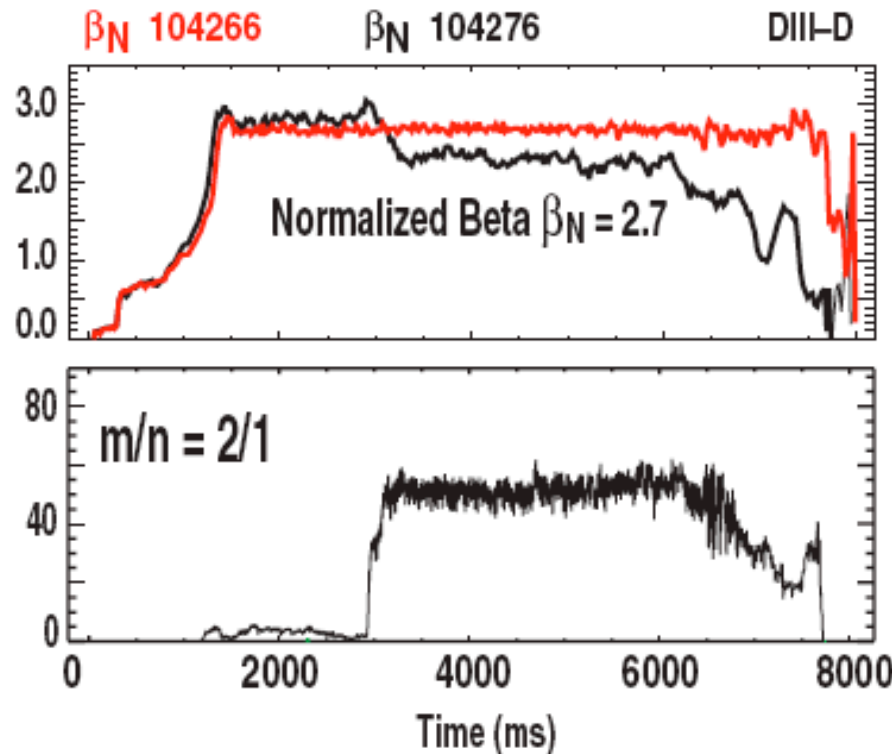
- $H_{89} \sim 3.5$, $HH_{98y2} \sim 2.2$, $\beta_N \sim 2$, $\beta_p \sim 2.9$, $f_{BS} \sim 80\%$ for $6\tau_E$ with full non-inductive CD
- Current profile was largely determined by the bootstrap current, and was nearly stationary



JT 60 also 80% bootstrap fraction



PRECISE CONTROL NEAR THE β -LIMIT IS THE KEY TO AVOIDING DISRUPTIONS



1. Need to operate close to stability limits

- Good control
- Knowledge of limits

High performance DIII-D discharge regulated 5% below 2/1 tearing limit for $35 \tau_E$ (6.3 seconds)

2. Mitigation of disruption consequences massive gas puff or pellets

- No runaway electrons
- Reduced halo currents and forces on structural components
- Reduced heat pulses to the divertor surfaces

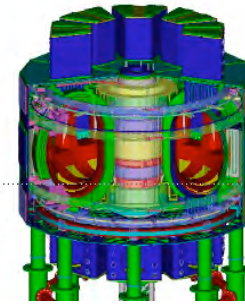
Four New Superconducting Tokamaks will Address Steady-State Advanced Tokamak Issues in Non-Burning Plasmas



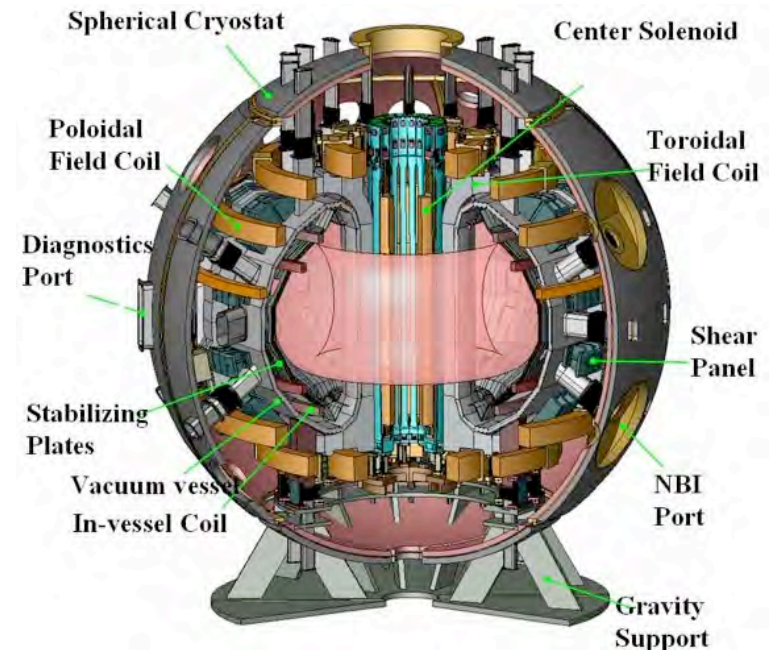
EAST: $R = 1.7\text{m}$, 2MA , 2006



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

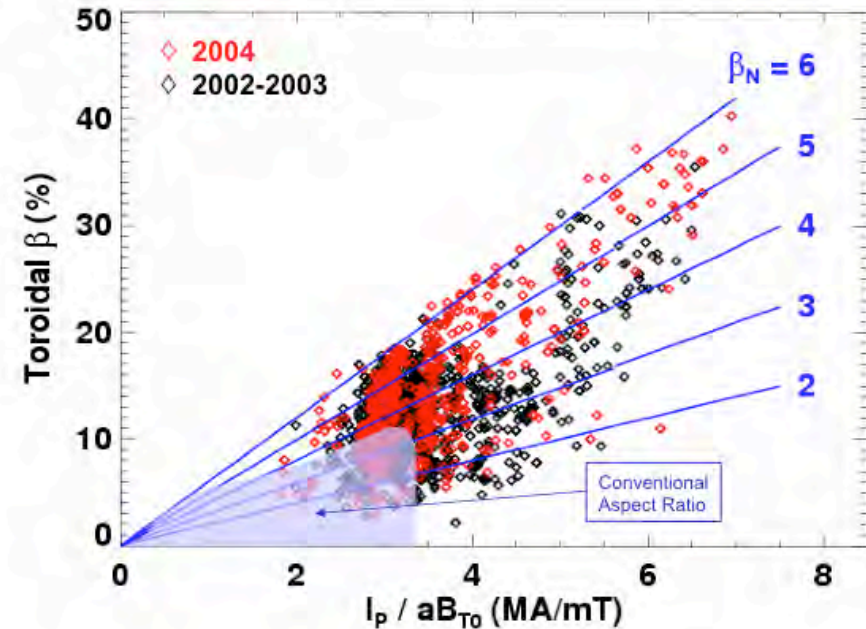
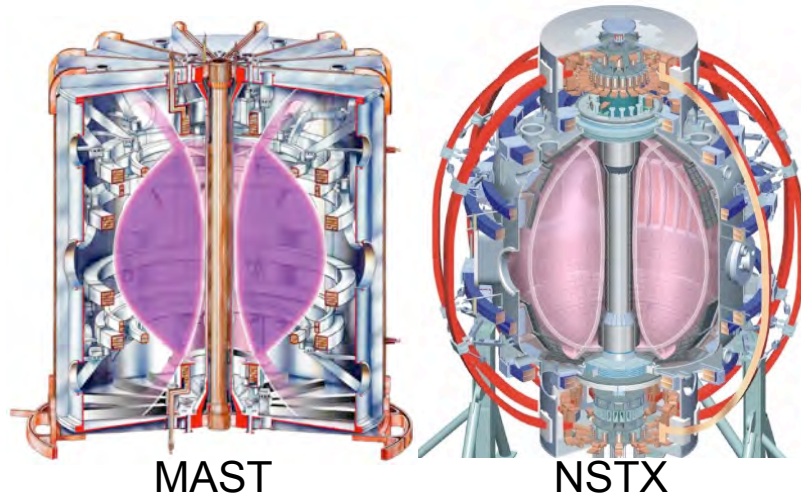


SST-1: $R = 1.1\text{m}$, 0.22MA , 2008



JT-60SA: $R = 3\text{m}$, 5.5 MA , 2014

Optimizing the 2-D Geometry of a Tokamak



- Higher β -limits at lower aspect ratio recognized in mid 1960s
- $\beta_t \approx 40\%$ achieved in START 1991-96 and NSTX 2004
- What is the optimum aspect ratio for overall system performance?
- Very Low aspect ratio may allow a Cu TF coil engineering solution in a D-T environment

The Stellarator/Helical (3-D) Systems

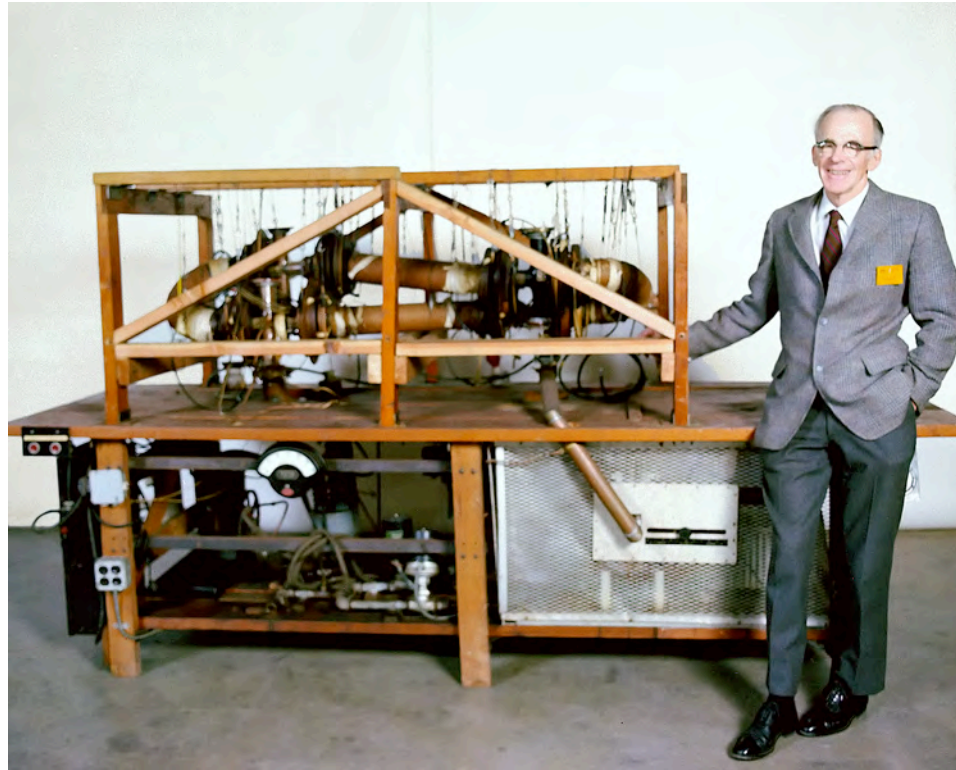
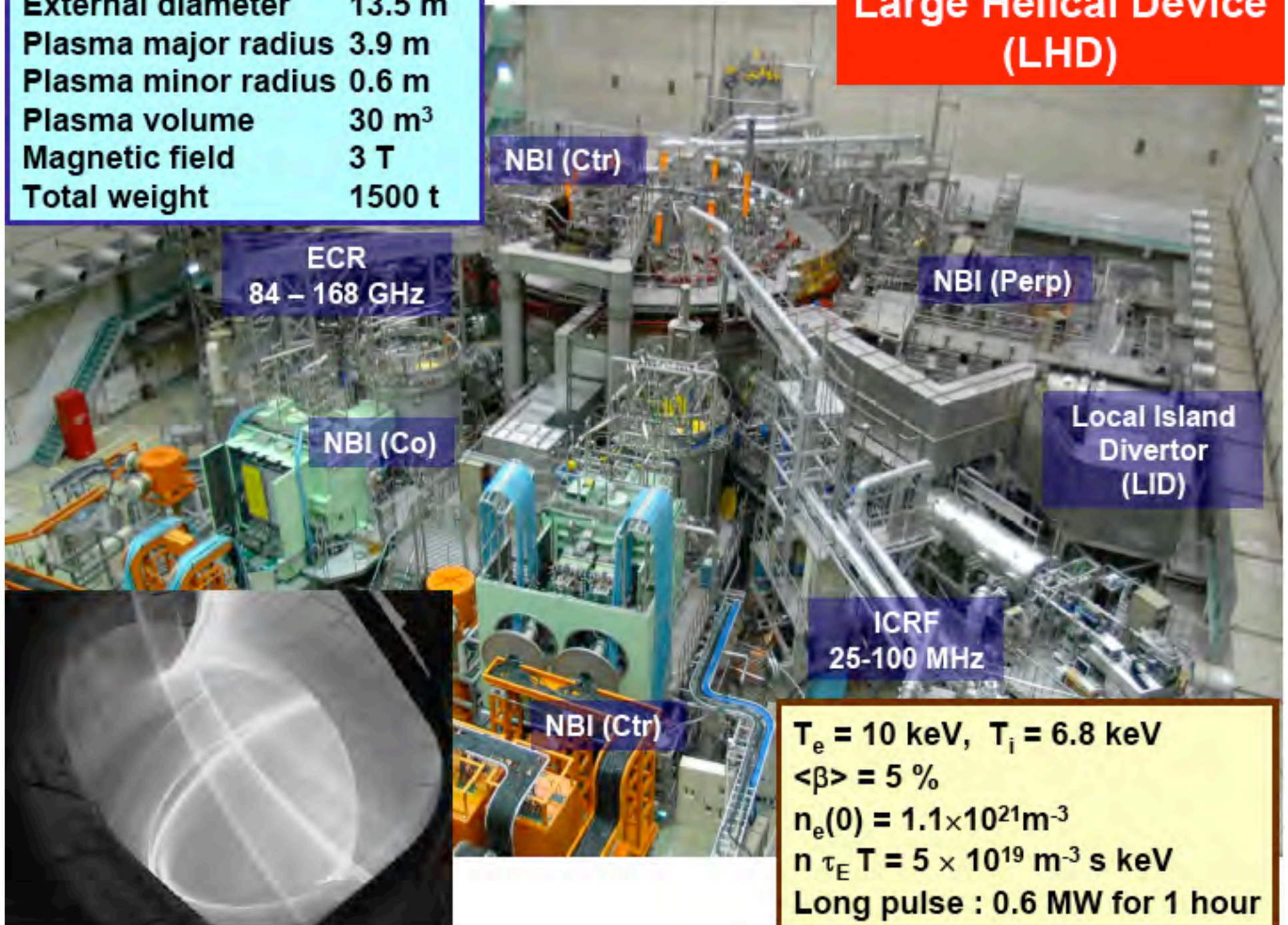


Figure 8 Stellarator (Model A ~ 1954) and Spitzer (1993)

- 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.
- PPPL Model C - converted to tokamak in 1969, and the main stellarator effort was₃₈ carried forward by IPP and Japan Univ's/NIFS through the 70s and 80s.

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

Large Helical Device (LHD)



NBI (Ctr)

ECR
84 – 168 GHz

NBI (Perp)

NBI (Co)

Local Island
Divertor
(LID)

ICRF
25-100 MHz

NBI (Ctr)

$T_e = 10 \text{ keV}$, $T_i = 6.8 \text{ keV}$

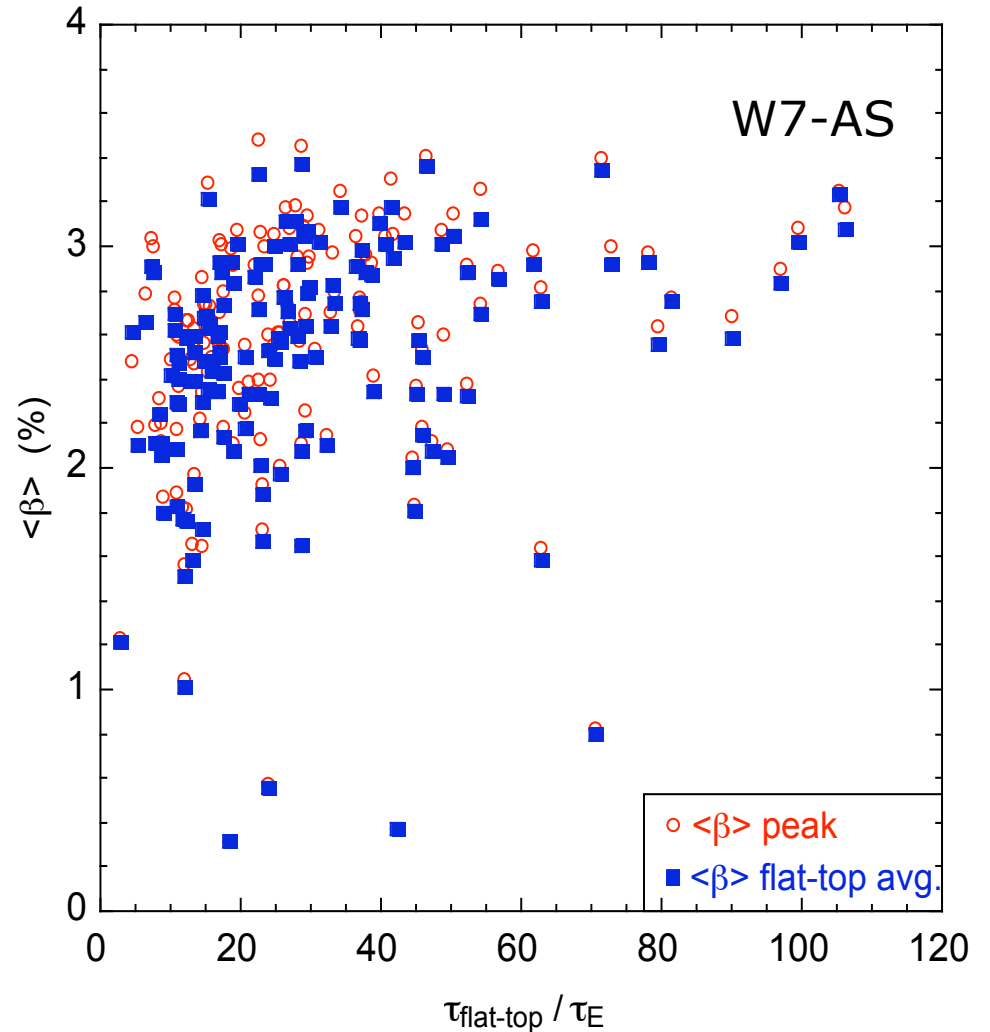
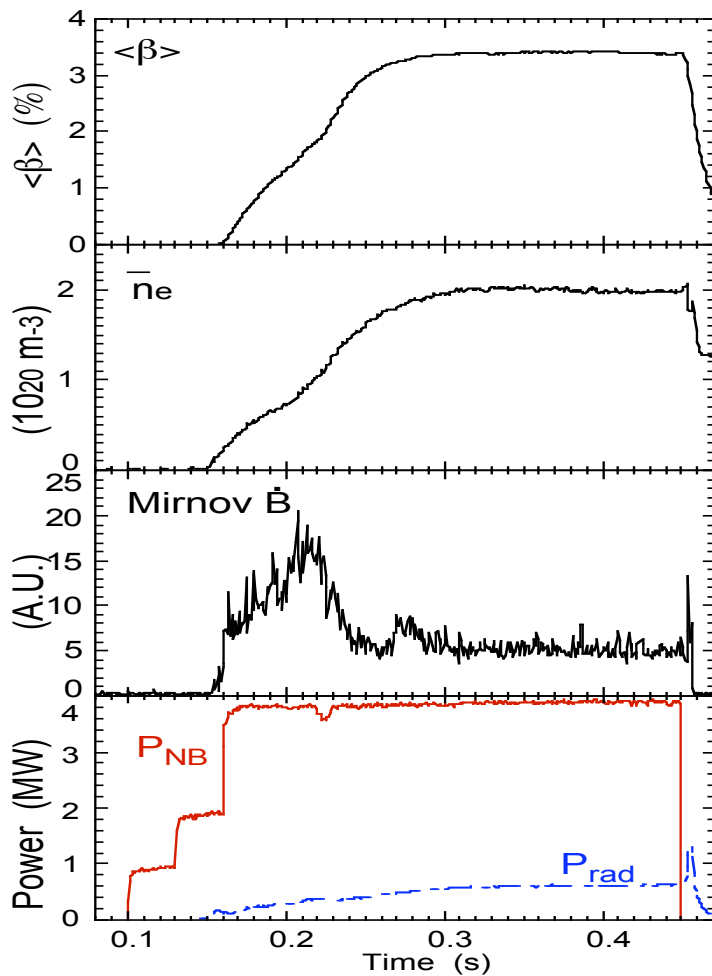
$\langle \beta \rangle = 5 \%$

$n_e(0) = 1.1 \times 10^{21} \text{ m}^{-3}$

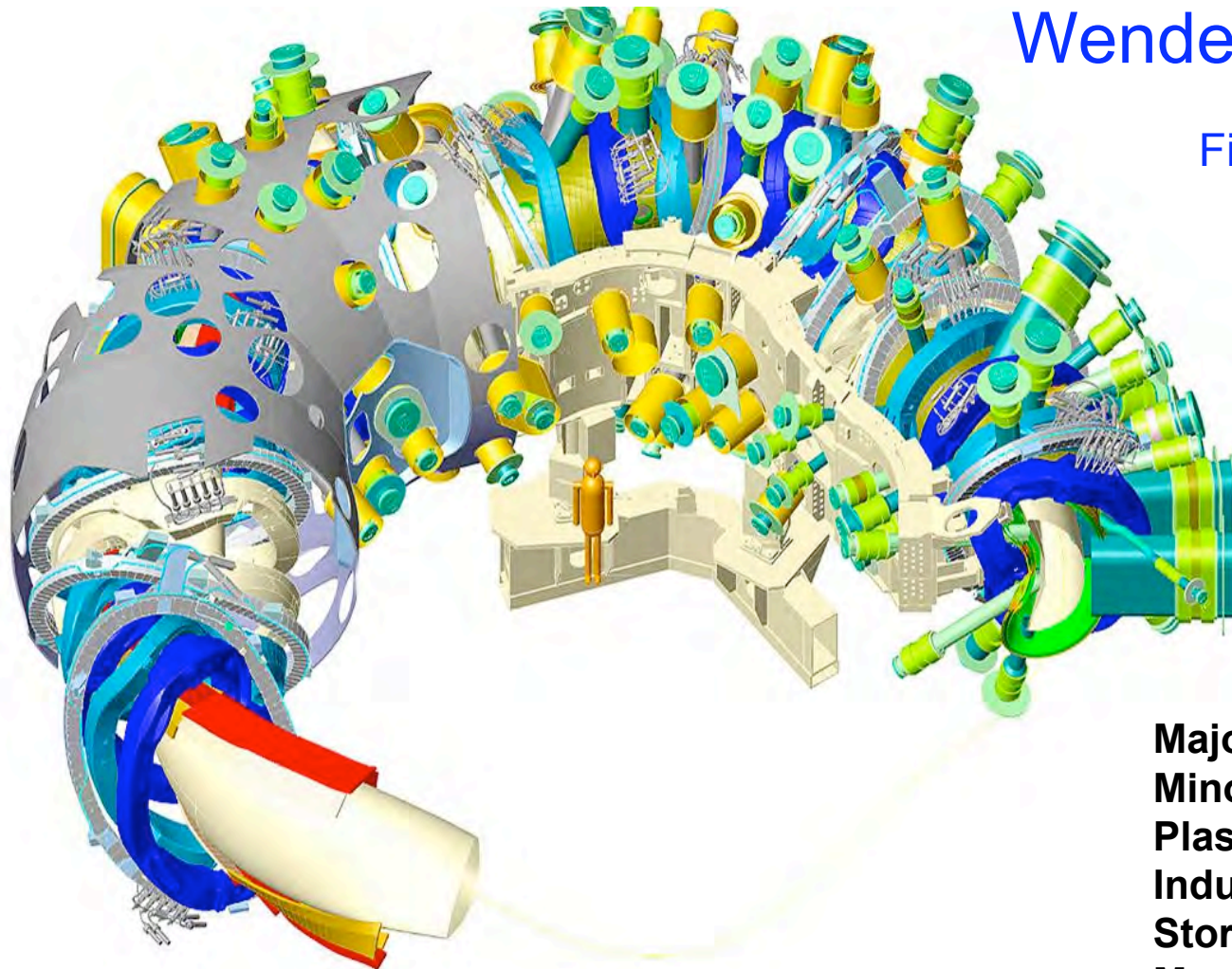
$n \tau_E T = 5 \times 10^{19} \text{ m}^{-3} \text{ s keV}$

Long pulse : 0.6 MW for 1 hour

Sustained Hi β in Partially Optimized Stellarator W7-AS



- W7-AS was the first stellarator device based on modular non-planar magnetic field coils
- demonstrated commonality with tokamak physics like access to H-mode confinement regime



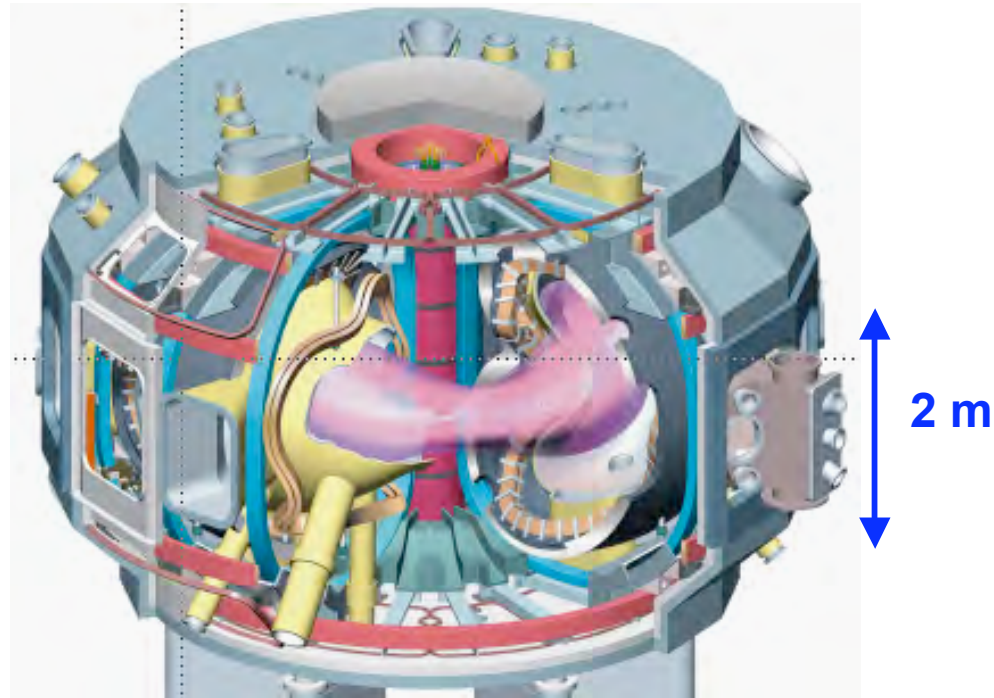
Wendelstein 7-X

First Plasma 2014

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.

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

Unfinished Business: Quasi-Axisymmetric Stellarators (NSCX)



- Intriguing opportunities for steady-state disruption-free operation
- 3-D with need for high precision leads to hardware complexity and higher costs
- How symmetric does quasi-symmetric have to be?
- What is the future in this area?

An International Team is Forged to Develop a New Energy Source



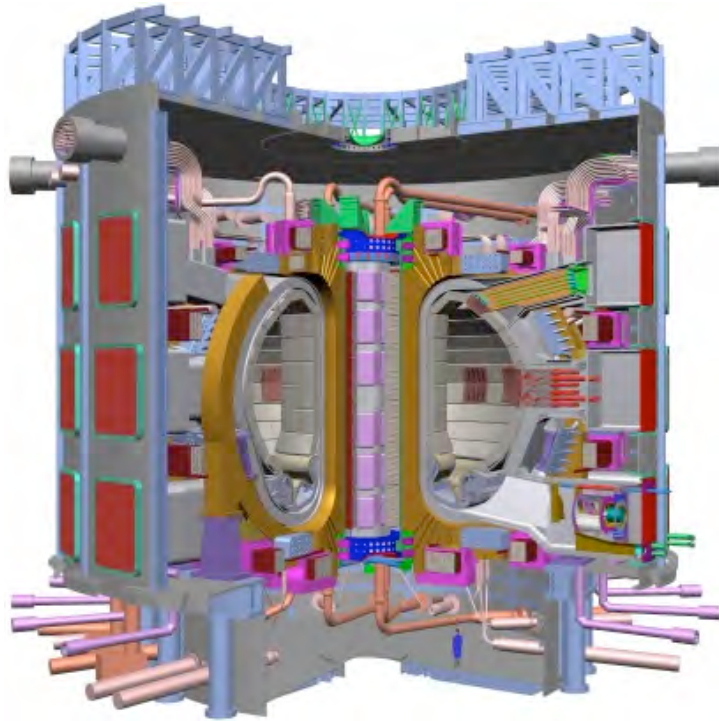
Gorbachev and Reagan



E. Velikhov

- 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

ITER is Now Underway



Reactor scale

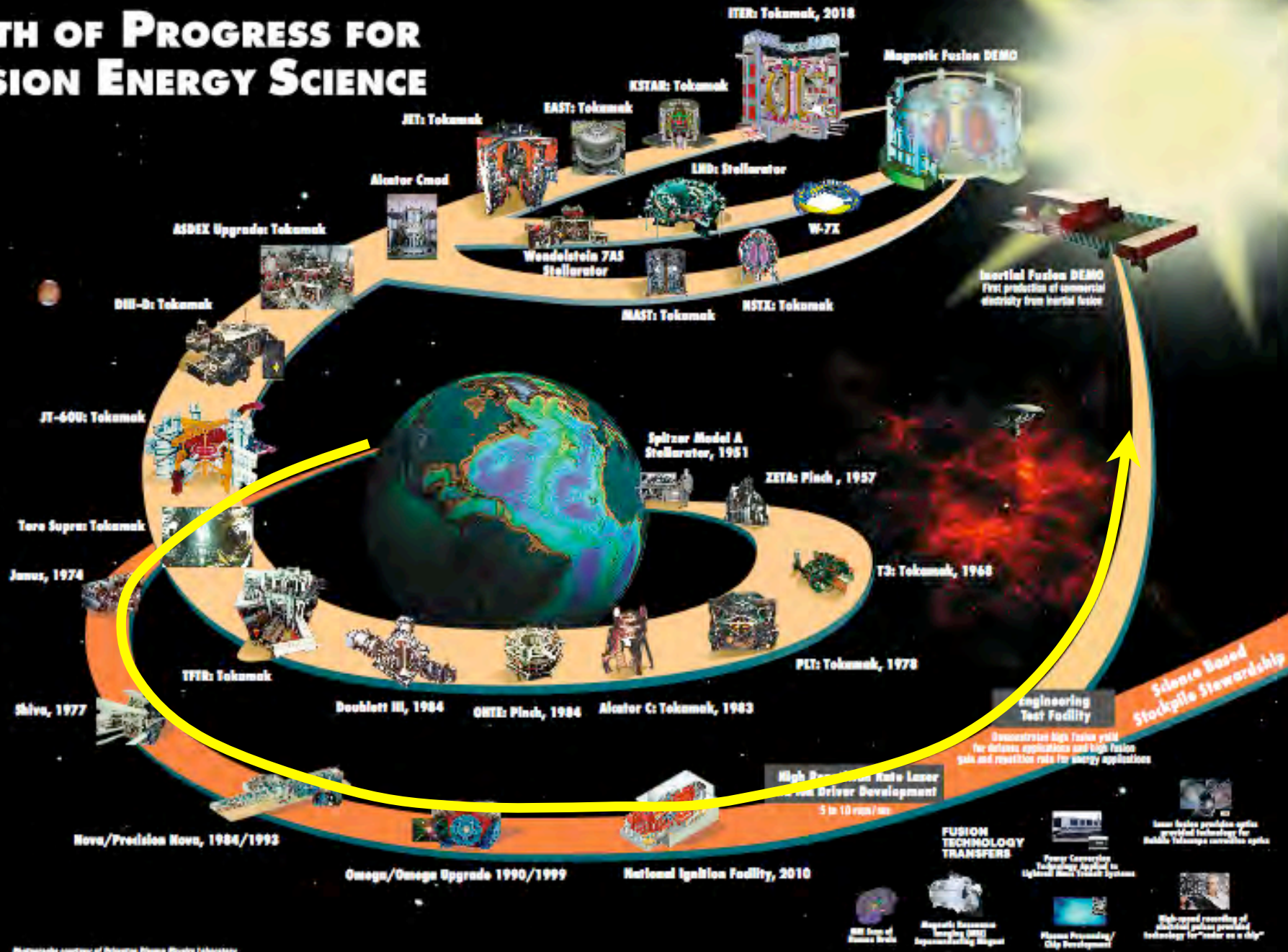


ITER Site Under Construction

First Plasma planned for 2018 ==> 2020

First DT operation planned for ~2022 ==> 2025

PATH OF PROGRESS FOR FUSION ENERGY SCIENCE



Science Based Stockpile Stewardship

Photographs courtesy of Princeton Plasma Physics Laboratory, Lawrence Livermore National Laboratory and General Atomics



... developing safe uses of atomic energy

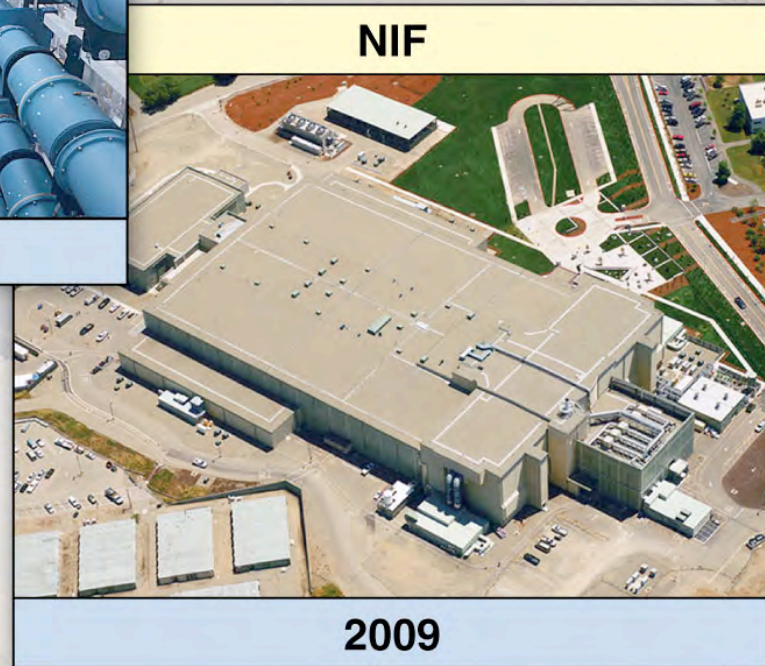
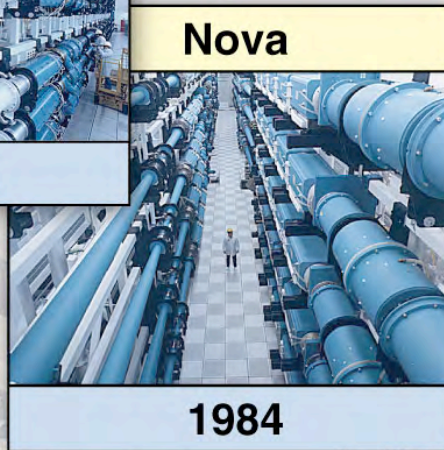
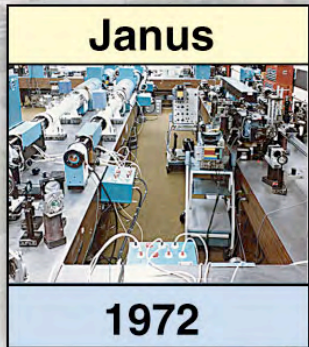
Inertial Confinement Fusion, Early Days

- 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.

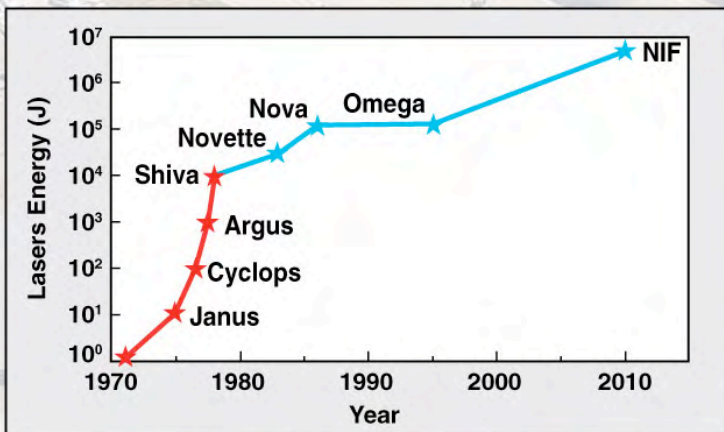
Construction of NIF/LMJ - ICF Burning Plasmas

- 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.

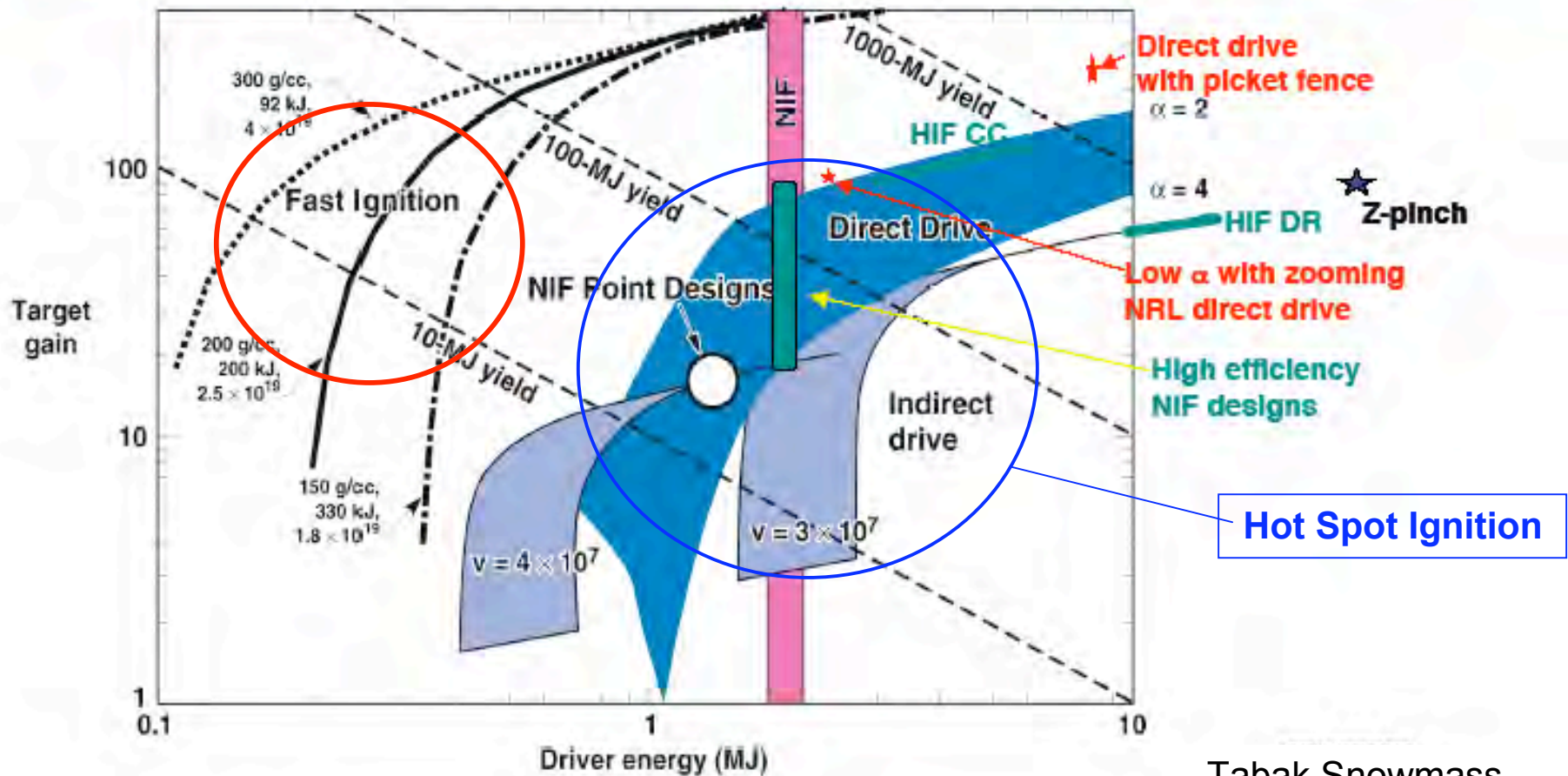
NIF Enabled by Rapid Advance in Laser Technology



- Glass laser energy has increased 10^6
- Fusion energy will need:
 - increased efficiency
 - increased repetition rate



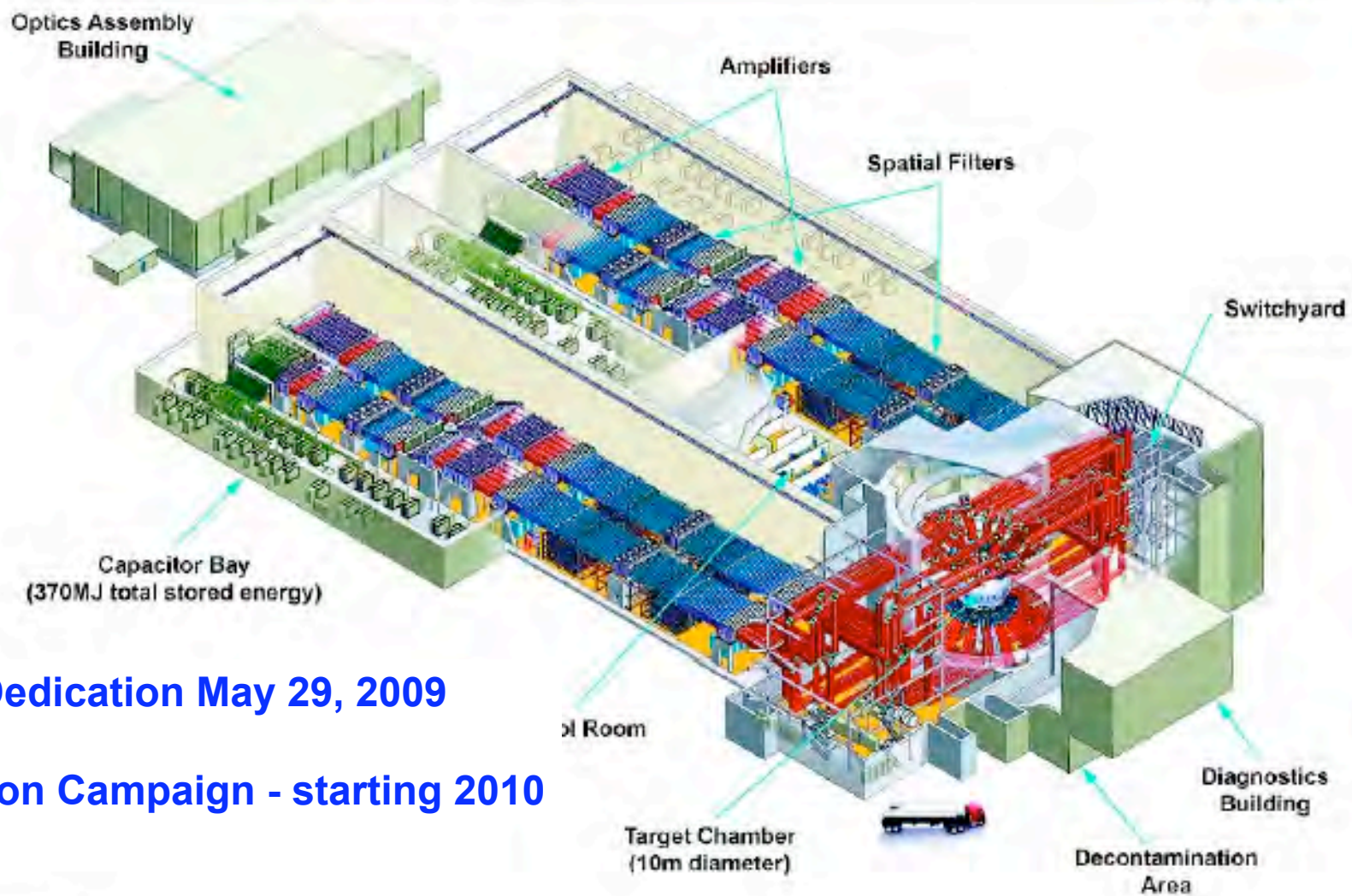
Target Designs with Varying Degrees of Risk Provide Adequate Gain for all Driver Concepts



Tabak Snowmass

FI Expt's -
Omega, FIREX,
HIPER

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



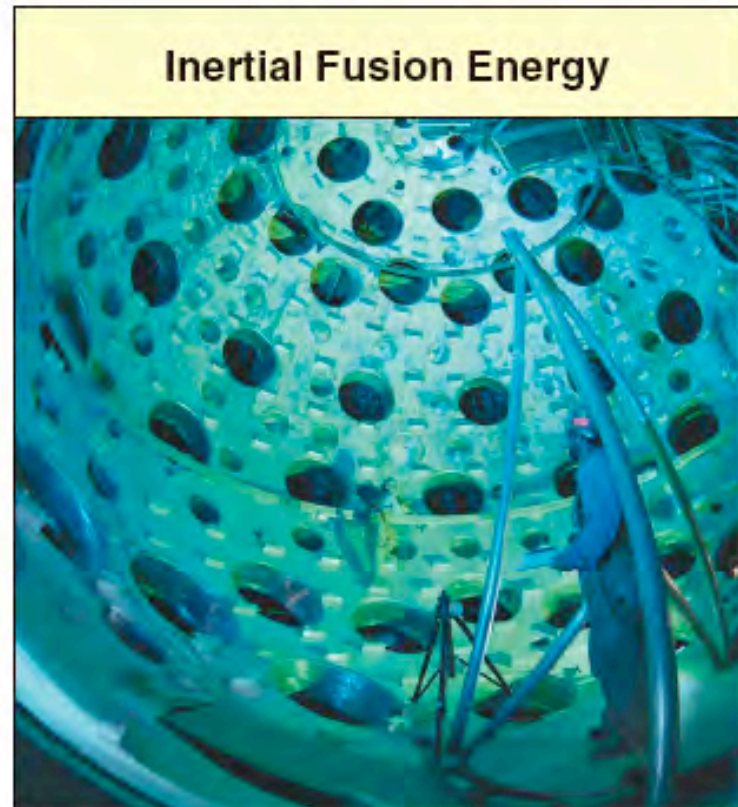
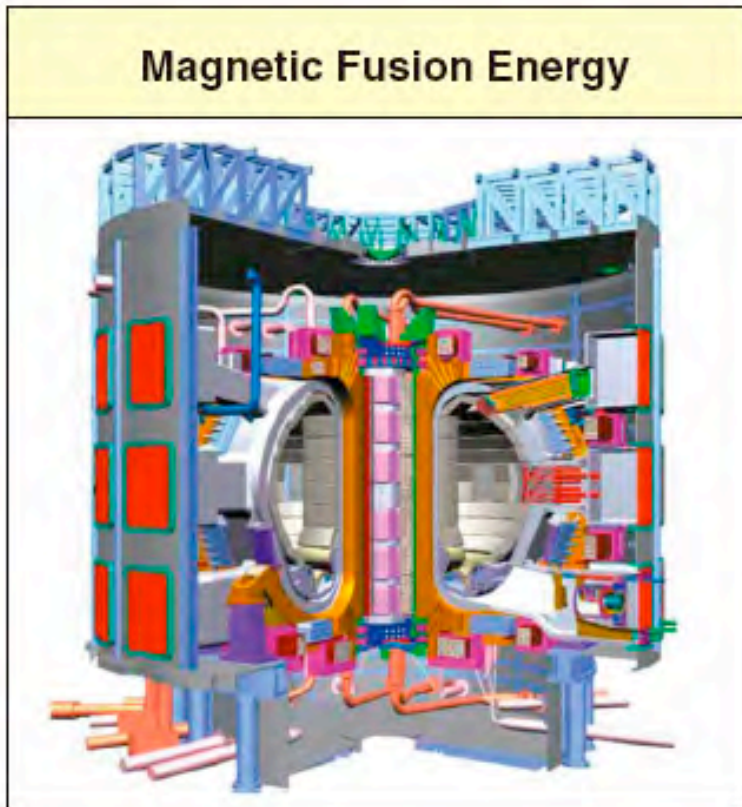
NIF Dedication May 29, 2009

Ignition Campaign - 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.

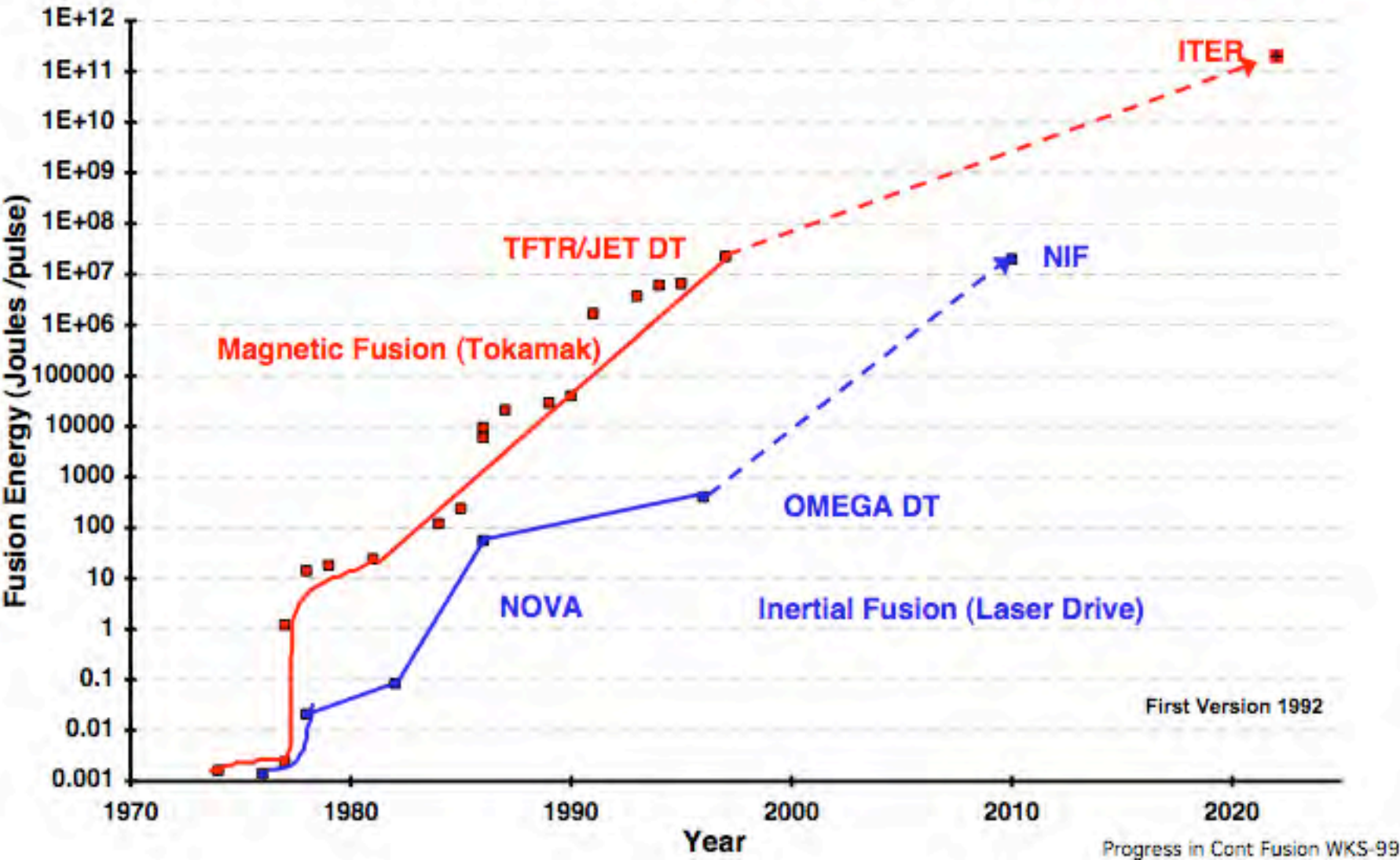
Facilities to Produce Fusion Energy are under Construction



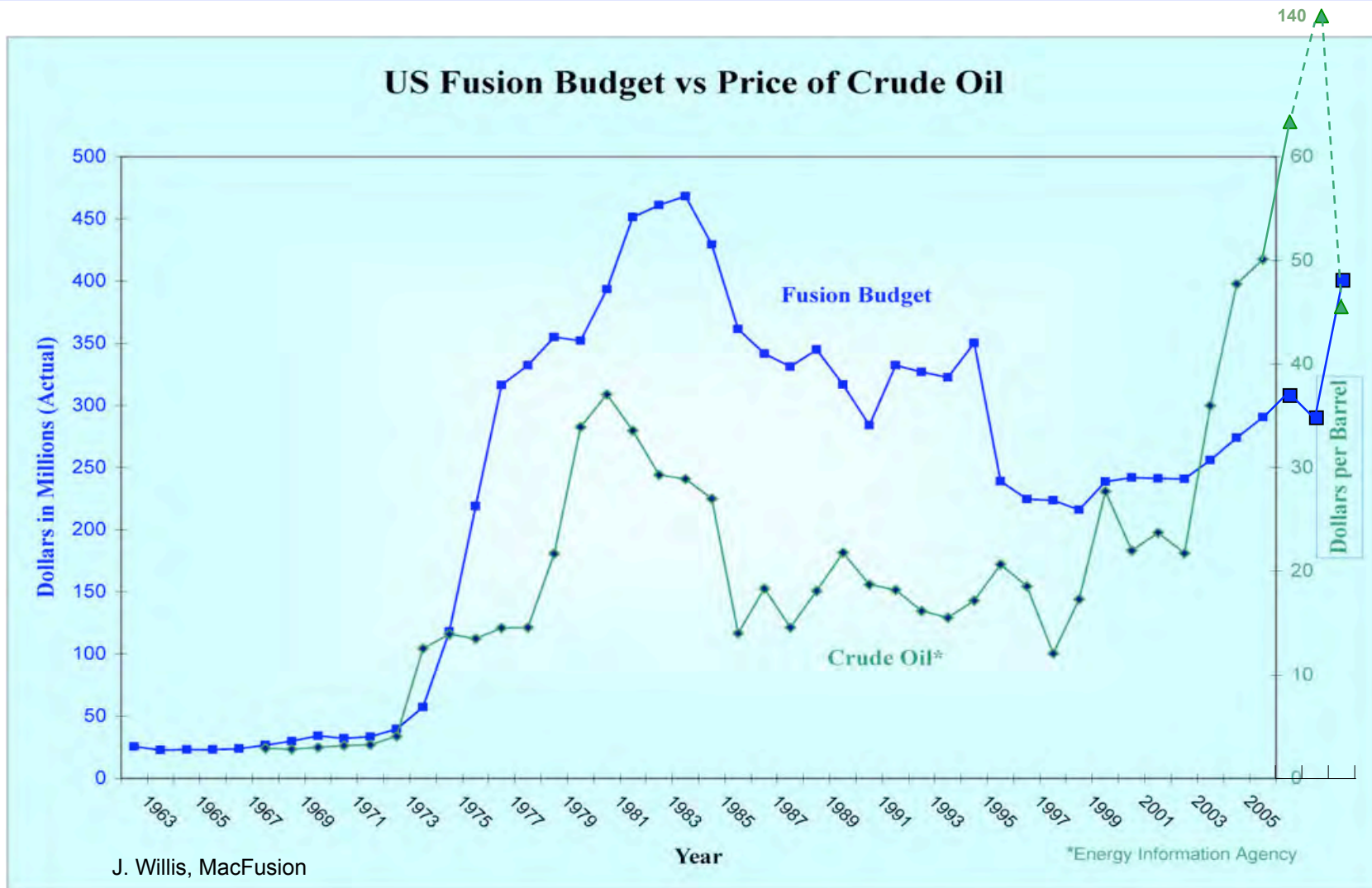
	ITER	
First D-T		~2022
Fusion Gain, Q		10
Fusion Energy/pulse		200,000 MJ

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

NIF and ITER will Extend Progress in Fusion Energy

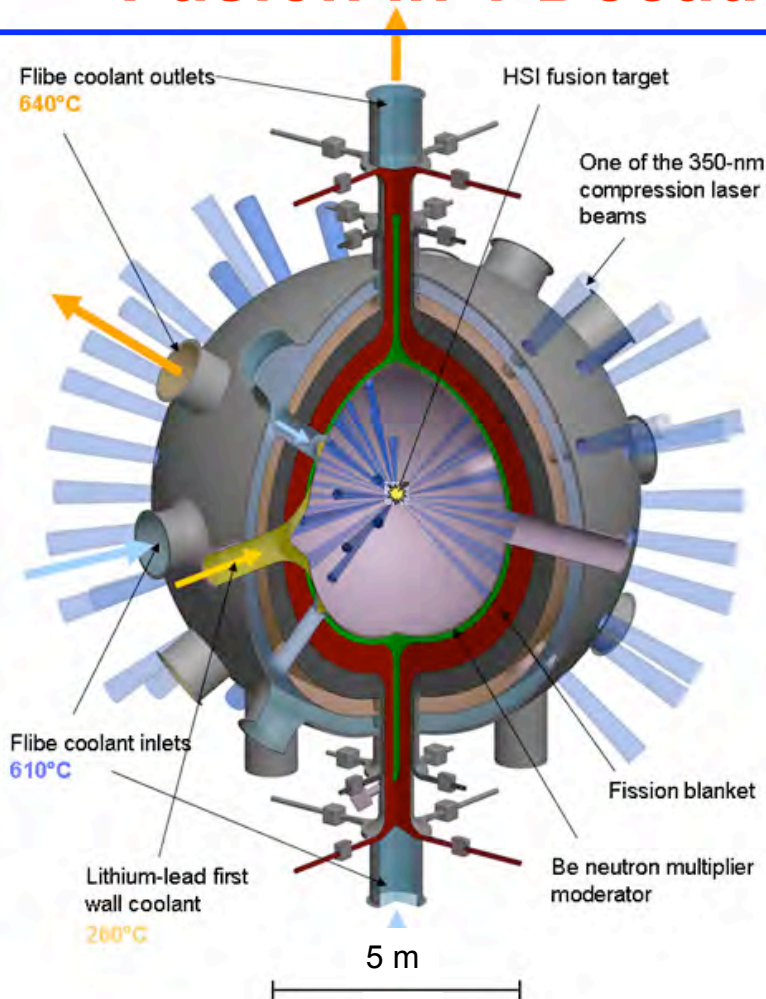


Is Fusion Prepared for a Major Next Step if Opportunity Knocks Again?

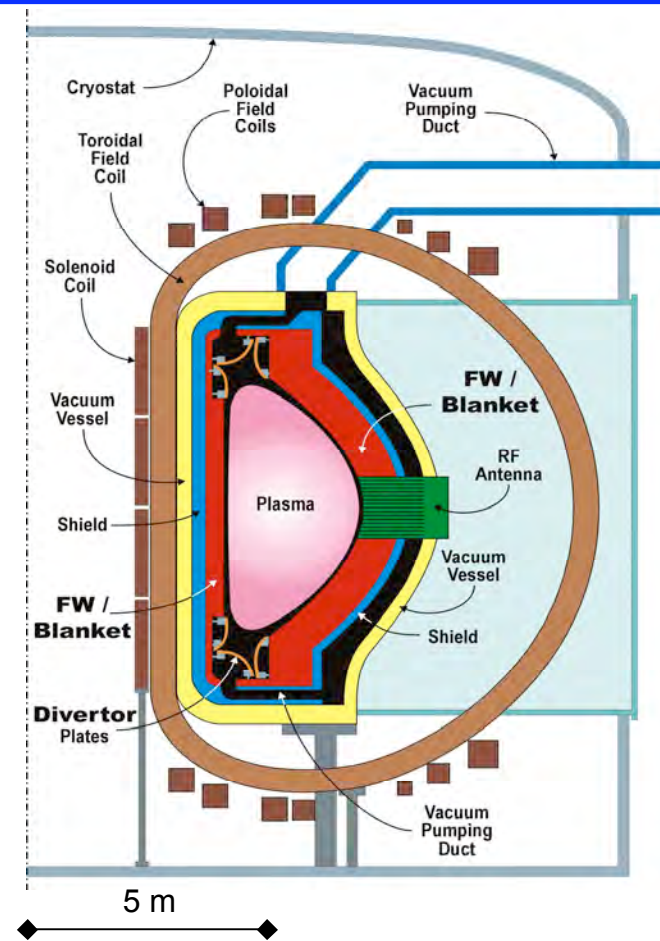


Fusion in 1 Decade

Fusion in 3 Decades



LIFE



DEMO

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

First D-T Power	~2025+15
Fusion Gain, Q	20 - 45
Fusion Power	2,500 MW ₅₅

Concluding Thoughts

- By any measure magnetic fusion has made enormous progress during the past 50 years, and has established a solid technical basis for taking the next step(s) to burning plasmas.
- Unfortunately, magnetic fusion has missed some critical opportunities that have delayed the program eg. 20 years ago with CIT.
- US MFE has drifted into a “treading water” phase, and is adding more small steps instead of taking a bold step forward.
- The MFE community needs a compelling vision to make a major step forward within a decade and establish the credibility of magnetic fusion. The clock is ticking and so is NIF.

Even Uncle Sam is getting impatient!



**I want you to get on with fusion,
and get it done in my lifetime.**

Acknowledgements

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