Some Highlights on the Paths to Controlled Ignition and Gain in the Laboratory

Dale Meade
Fusion Innovation Research and Energy®
Princeton, NJ
United States of America

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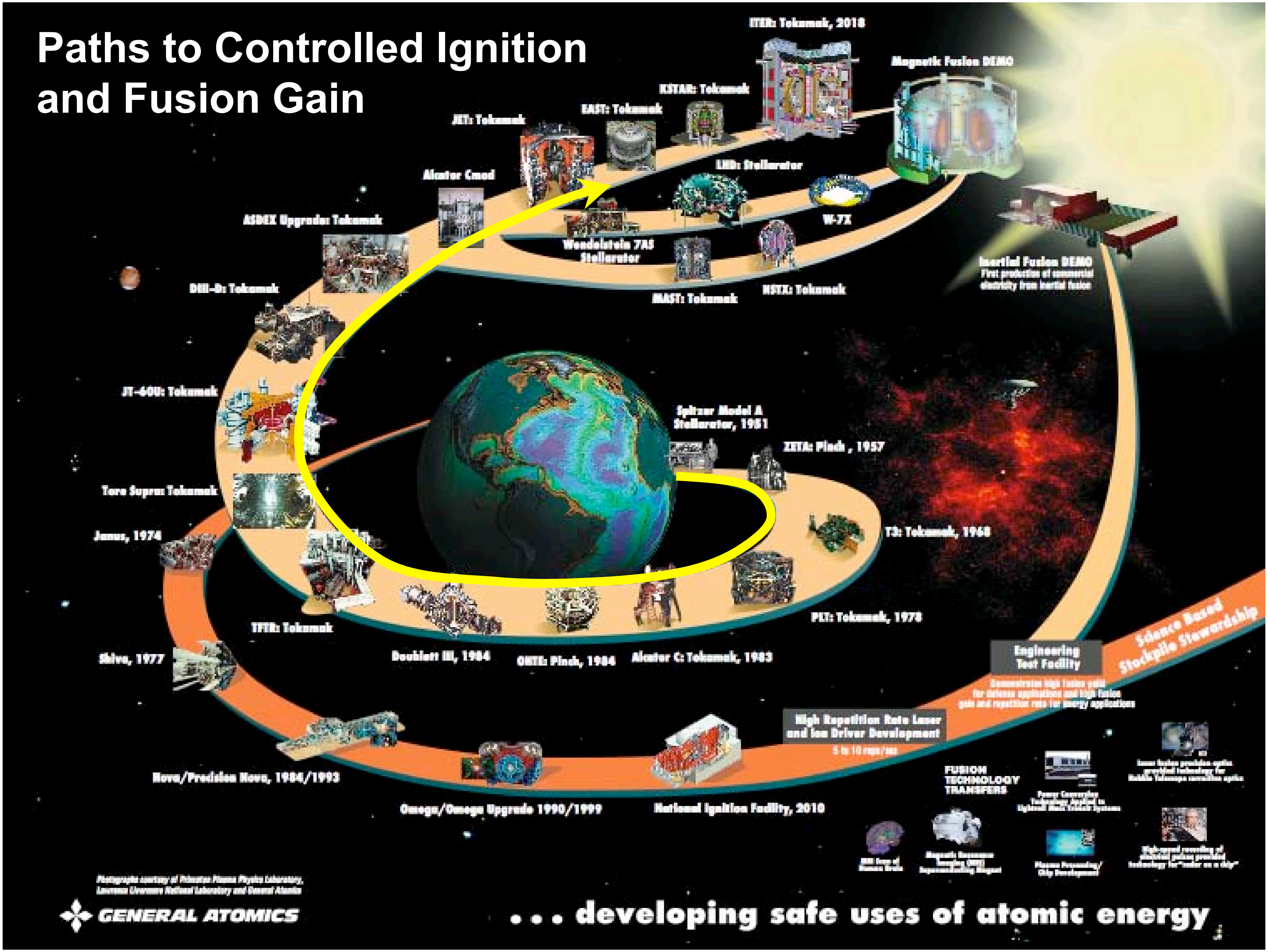
Paths to Controlled Ignition and Fusion Gain



Fusion Prior to Geneva 1958

- A period of rapid progress in science and technology
  - N-weapons, N-submarine, Fission energy, Sputnik, ...
- 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
  - 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 tried and ended up far from fusion conditions
  - Magnetic Fusion research in the U.S. declassified in 1958

Meeting Hall Geneva 1958

US Exhibit at Geneva 1958

UK Exhibit at Geneva 1958

Geneva 1958 - Fusion meets Sputnik

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 - Ohkawa/Kerst
  - 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

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

Increasing $B_{multipole}$

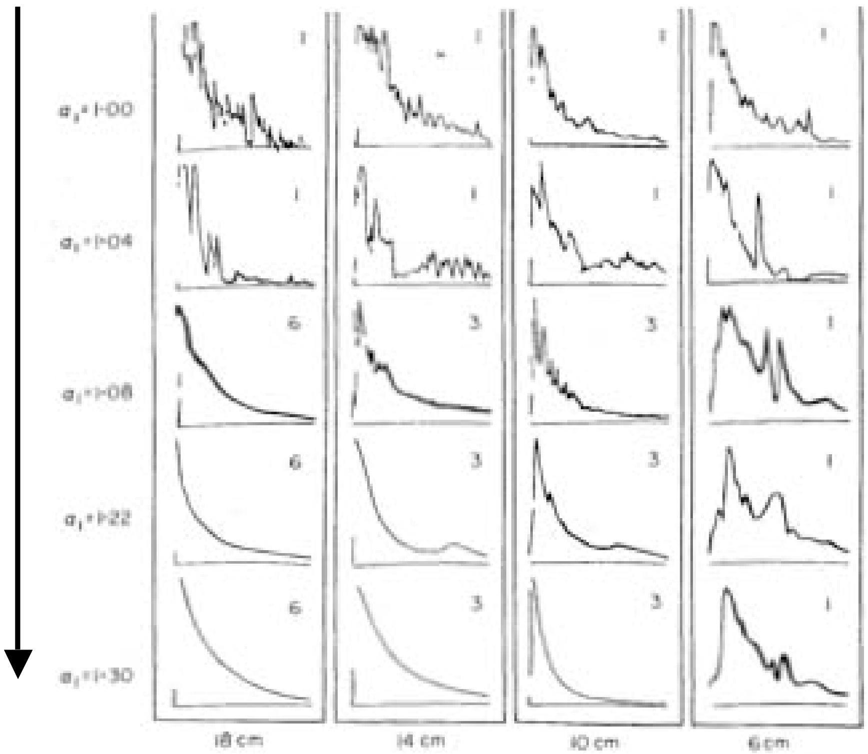
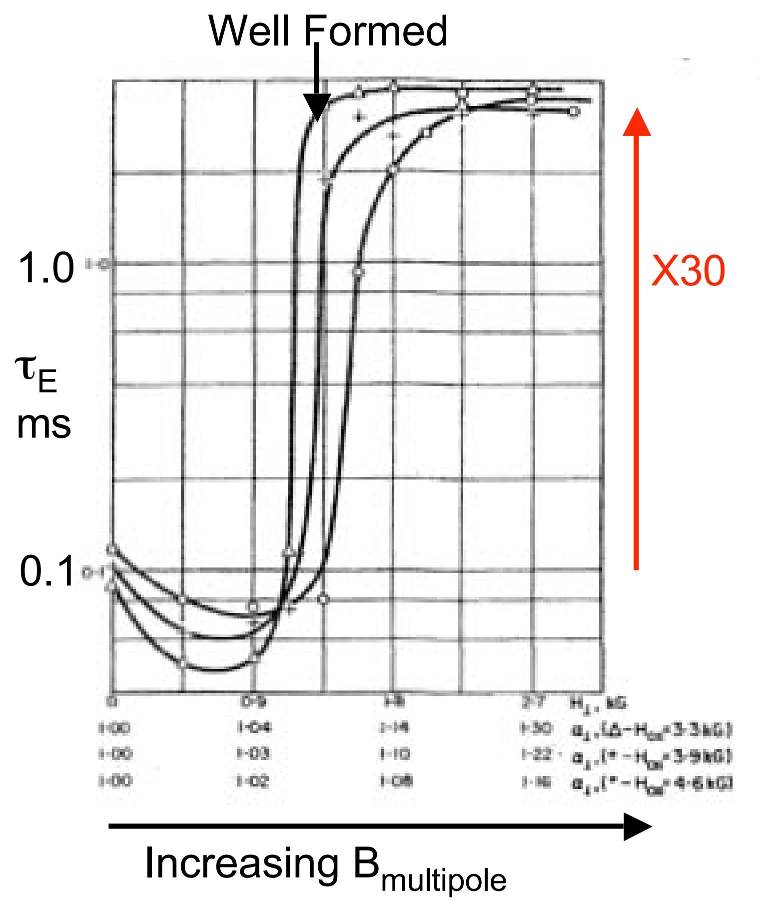


FIG. 8.—Oscillograms of ion current entering a Langmuir probe placed at various distances from the axis of the trap. (The figures in the right-hand corners of each oscillogram are the sweep lengths in milliseconds.)



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

1968-69 T-3 Breaks Bohm, Tokamaks Proliferate

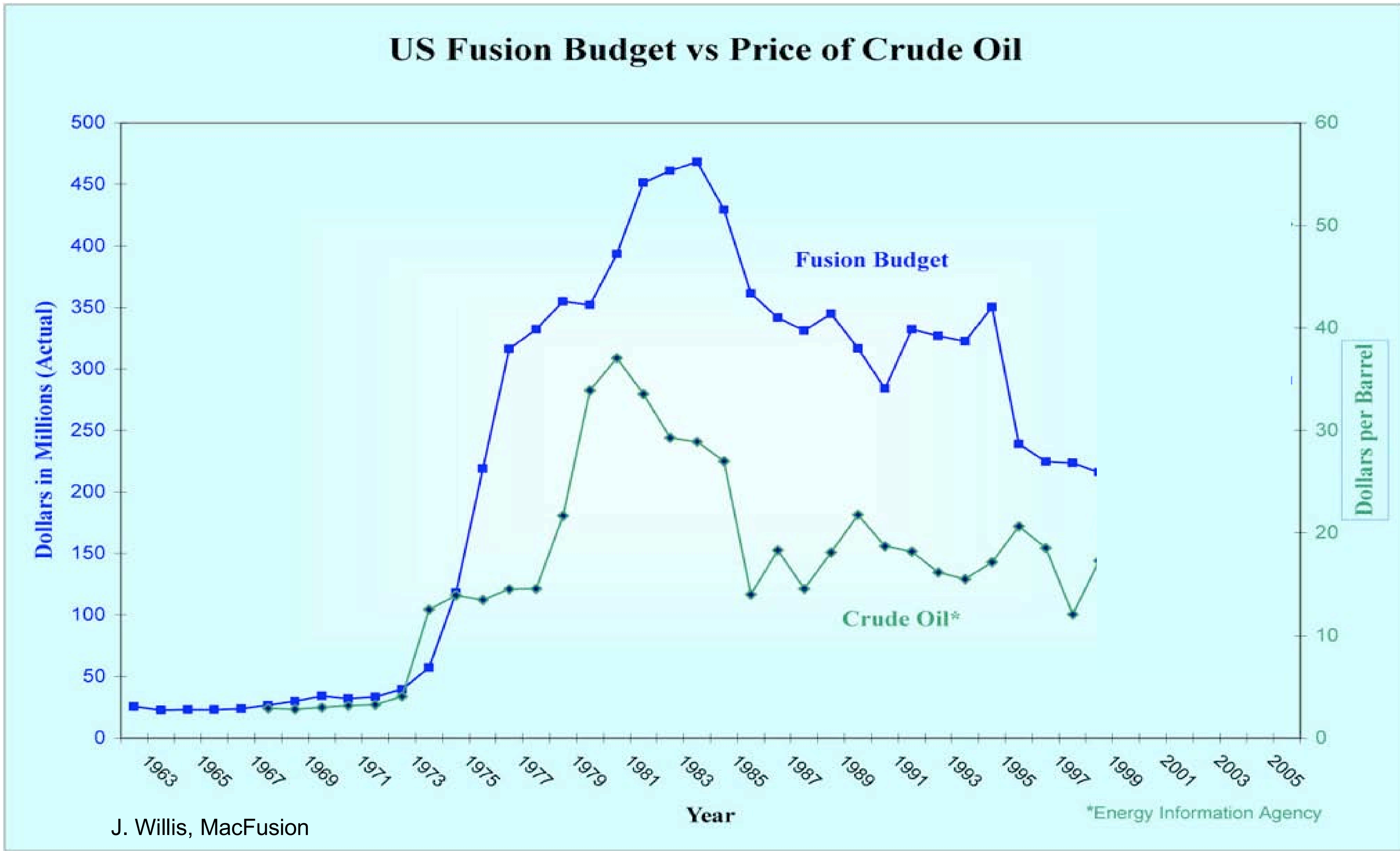
- Hints of a major advance at IAEA Novosibirsk 1968, but skeptics abound

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



Tokamak Optimization

- By the mid 80s (~ 1984)
  - It was clear from early system studies that tokamak performance would need to be improved, if the tokamak were to lead to an attractive fusion power source. Advanced Tokamak Initiative established by Ed Kintner 1979 following proposal by Toroidal Steering Com.
  - 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

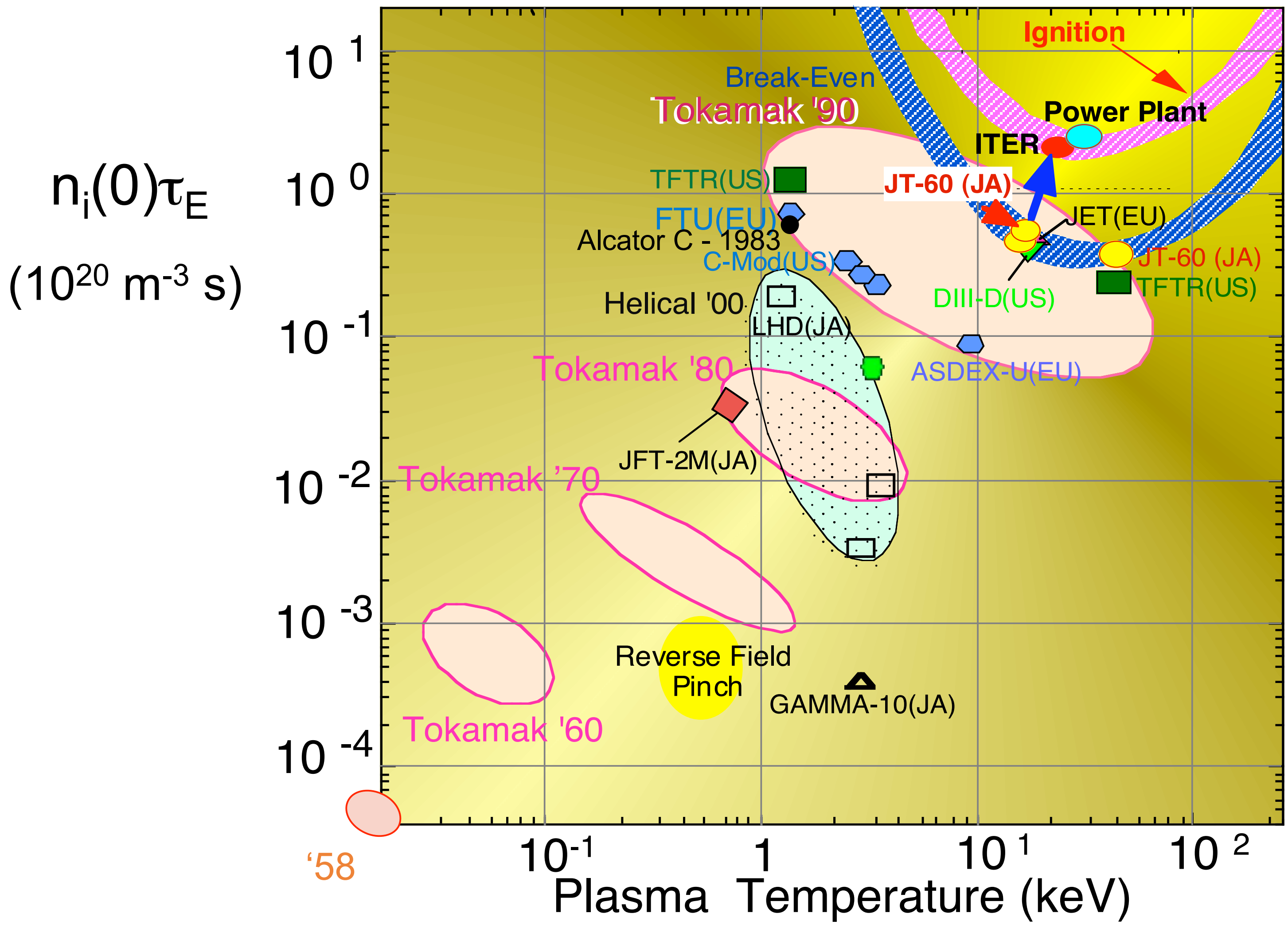
- After about 6 years of construction TFTR, JET and JT-60 began operation 1982-84.

- By the mid 80s, after 4 years of operation the plasma parameter range had been significantly extended
  - T_i~ 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. Note: MFTF-B construction was completed in 1986 demonstrating complex superconducting coil technology at large scale.

- Enabling Technology - Neutral beams, pellet injection, PFCs.

Fusion Temperatures Attained,
Fusion Confinement One Step Away



$n_i(0)\tau_E T_i$ increased by ~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
  - 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
  - Remote handling

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.

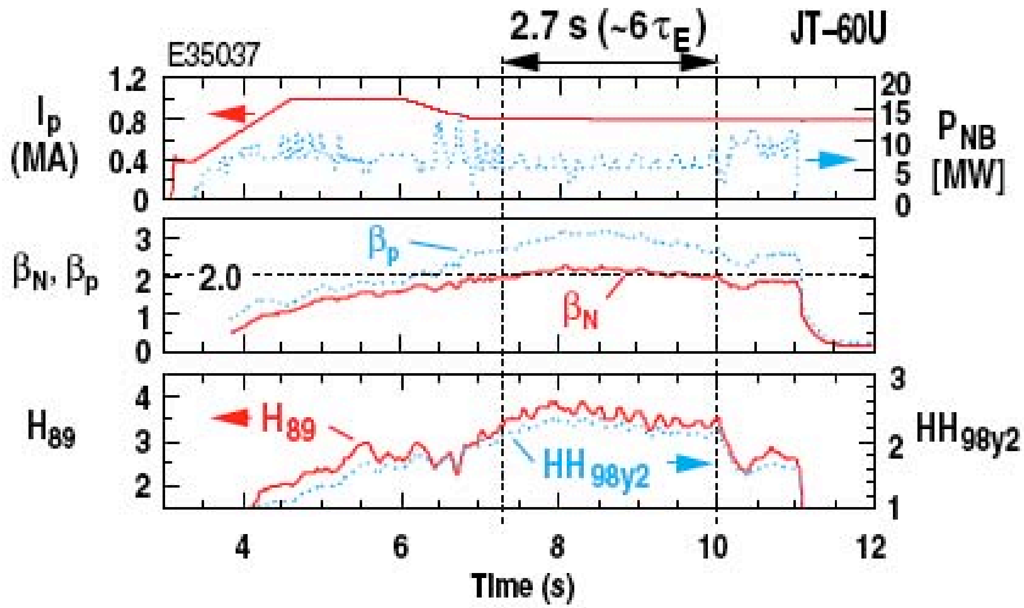
  - Effective removal of plasma exhaust and nuclear heat
    - Power density and distribution of removed power
    - Effect of self conditioned PFC on plasma behavior

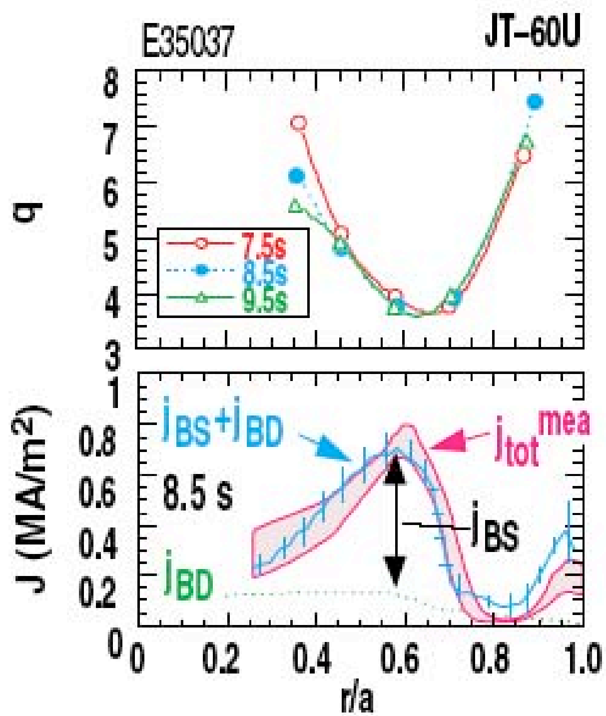
- Helical/Stellarator Resurgence
  - Confinement, beta approaching tokamak
  - Opportunities for configuration optimization

- Long Pulse Superconducting tokamaks - T-7, T-15, Tore Supra, TRIAM, EAST, KSTAR, SST-1, JT-60SA

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

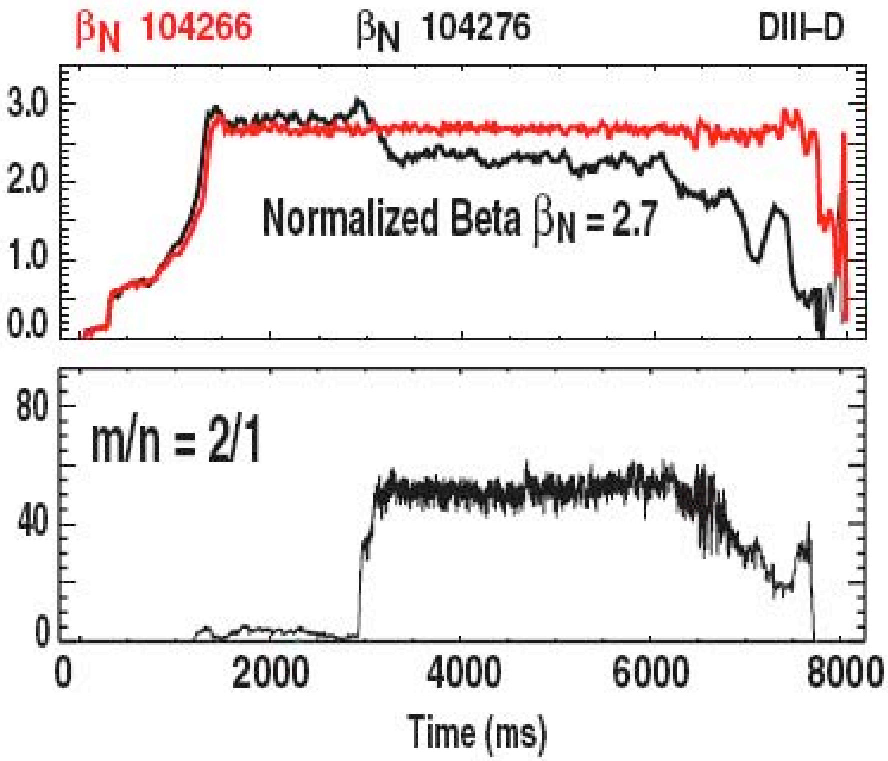
- H_{89}~3.5, HH_{98y2}~2.2, β_N~2, β_p~2.9, f_{BS}~80% for $6\tau_E$ with full non-inductive CD
- Current profile was largely determined by the bootstrap current, and was nearly stationary





JT 60 also 80% bootstrap fraction

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

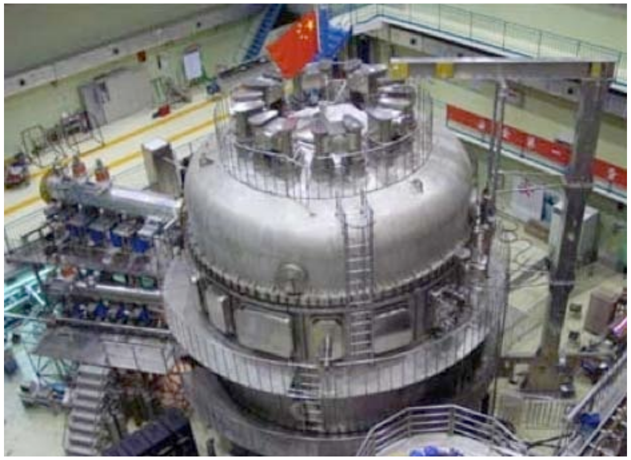


1. Need to operate close to stability limits
   - Good control
   - Knowledge of limits

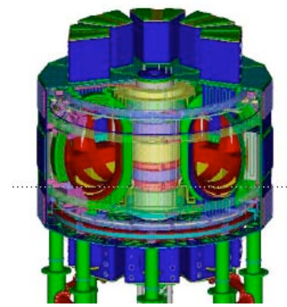
   High performance DIII–D discharge regulated 5% below 2/1 tearing limit for 35 τ_E (6.3 seconds)

2. Mitigation of disruption consequences massive gas puff or pellets
   - No runaway electrons
   - Reduced halo currents and forces on structional components
   - Reduced heat pulses to the divertor surfaces

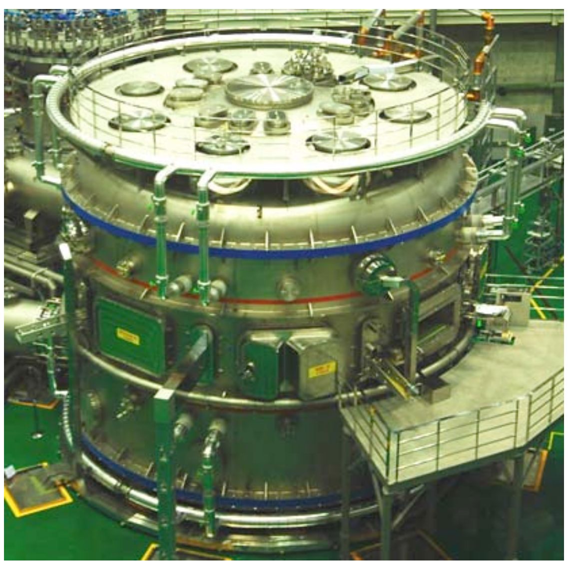
Four New Superconducting Tokamaks will Address Steady-State Advanced Tokamak Issues in Non-Burning Plasmas



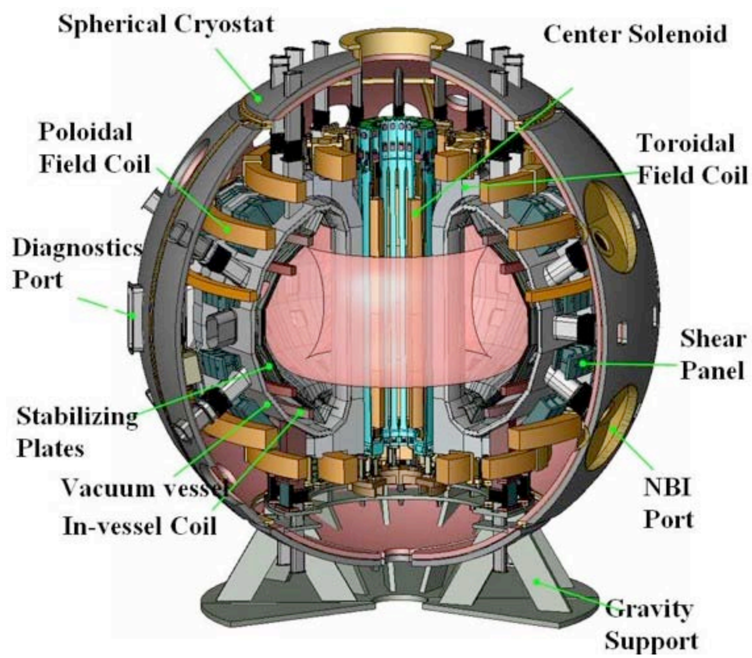
EAST: R = 1.7m, 2MA, 2006



SST-1: R =1.1m, 0.22MA, 2008

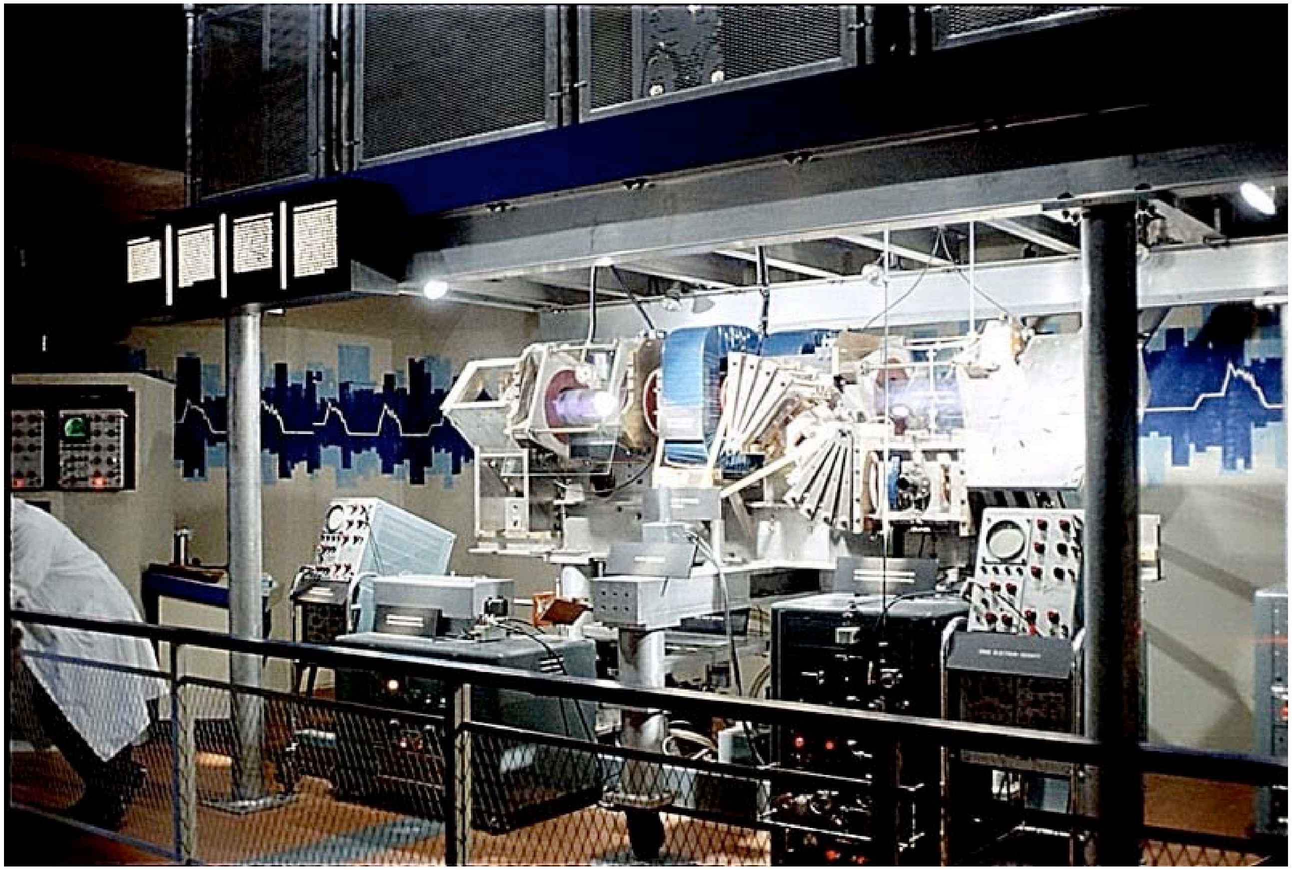


KSTAR: R = 1.8m, 2MA, 2008



JT-60SA: R = 3m, 5.5 MA, 2014

The Stellarator/Helical (3-D) Systems



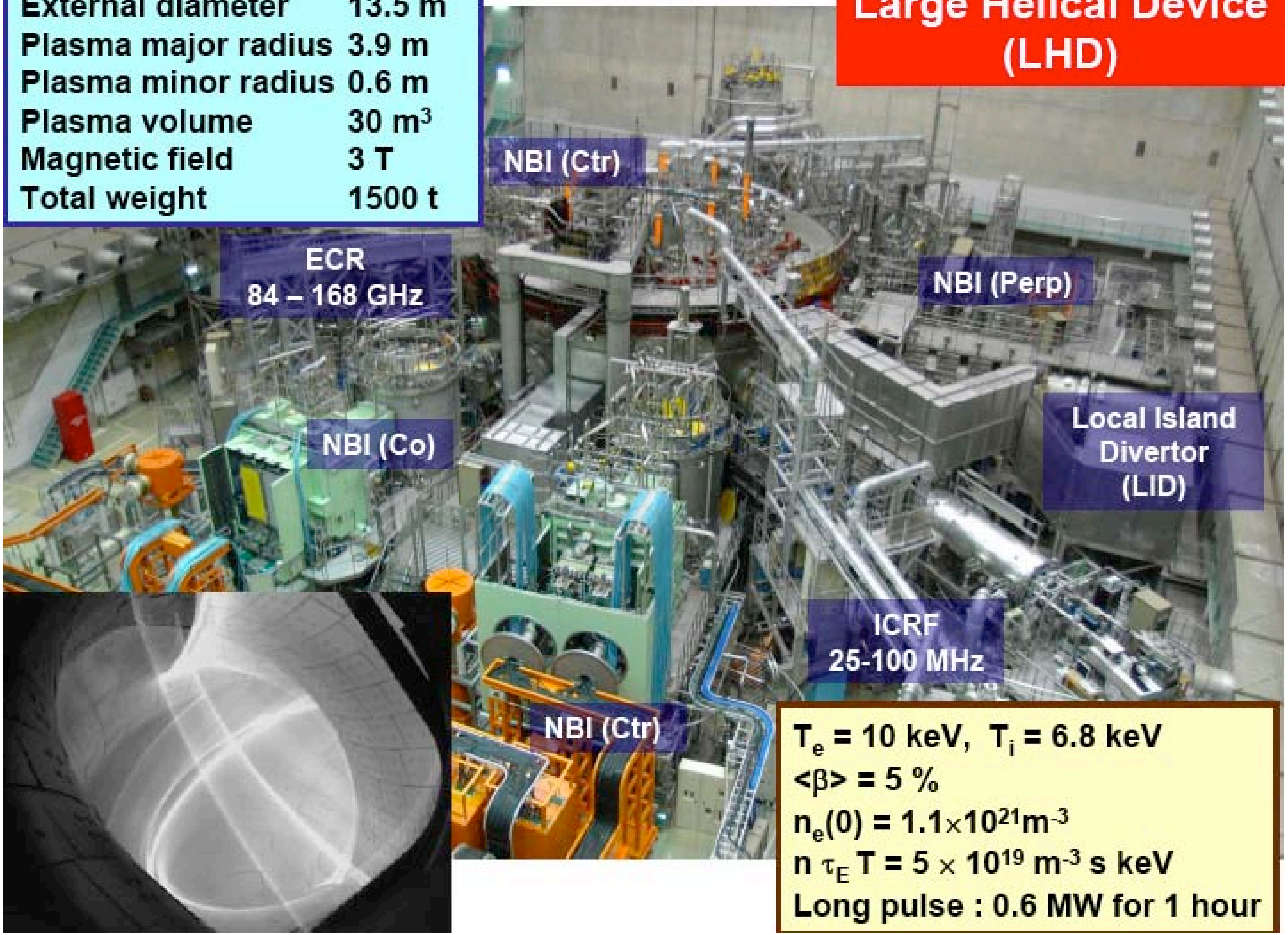
Stellarator (Model B-2) at Geneva 1958 (by F. Chen attendee)

• 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 was carried forward by IPP and Japan Univ's/NIFS through the 70s and 80s.

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



T_e = 10 keV, T_i = 6.8 keV

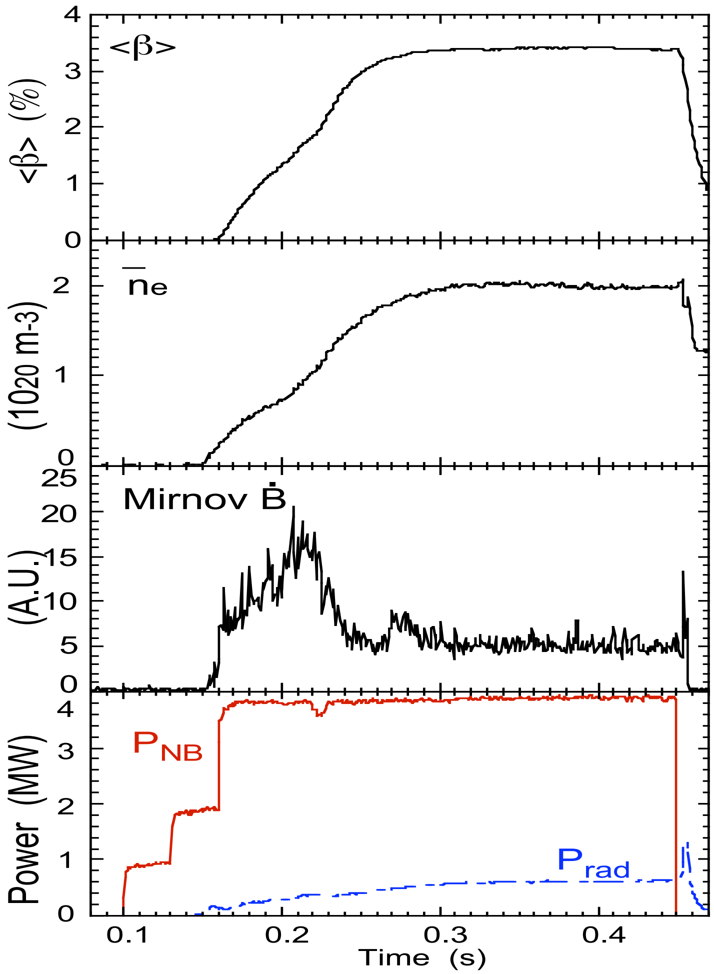
$\langle\beta\rangle$ = 5 %

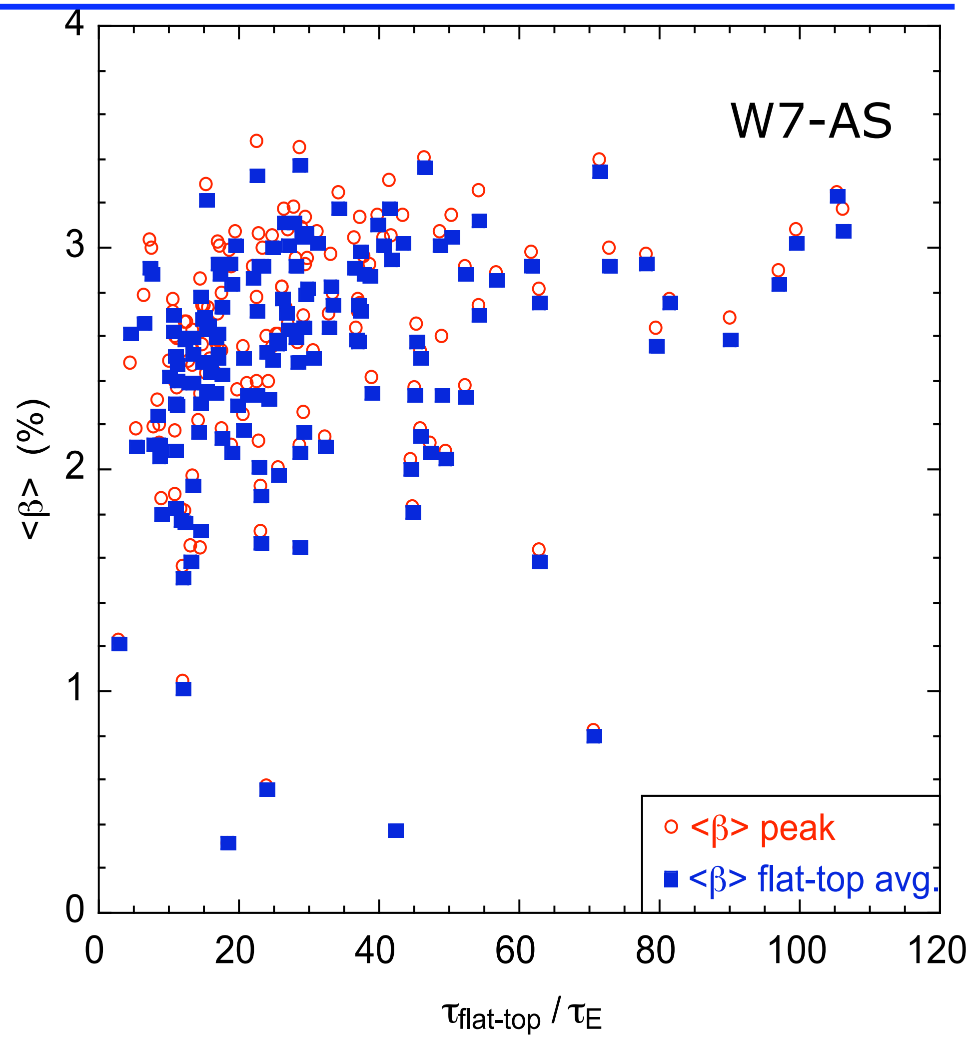
$n_e(0) = 1.1\times10^{21} m^{-3}$

$n\,\tau_E\,T = 5\times10^{19}\ m^{-3}$ s keV

Long pulse : 0.6 MW for 1 hour

Sustained Hi β in Partially Optimized Stellarator W7-AS

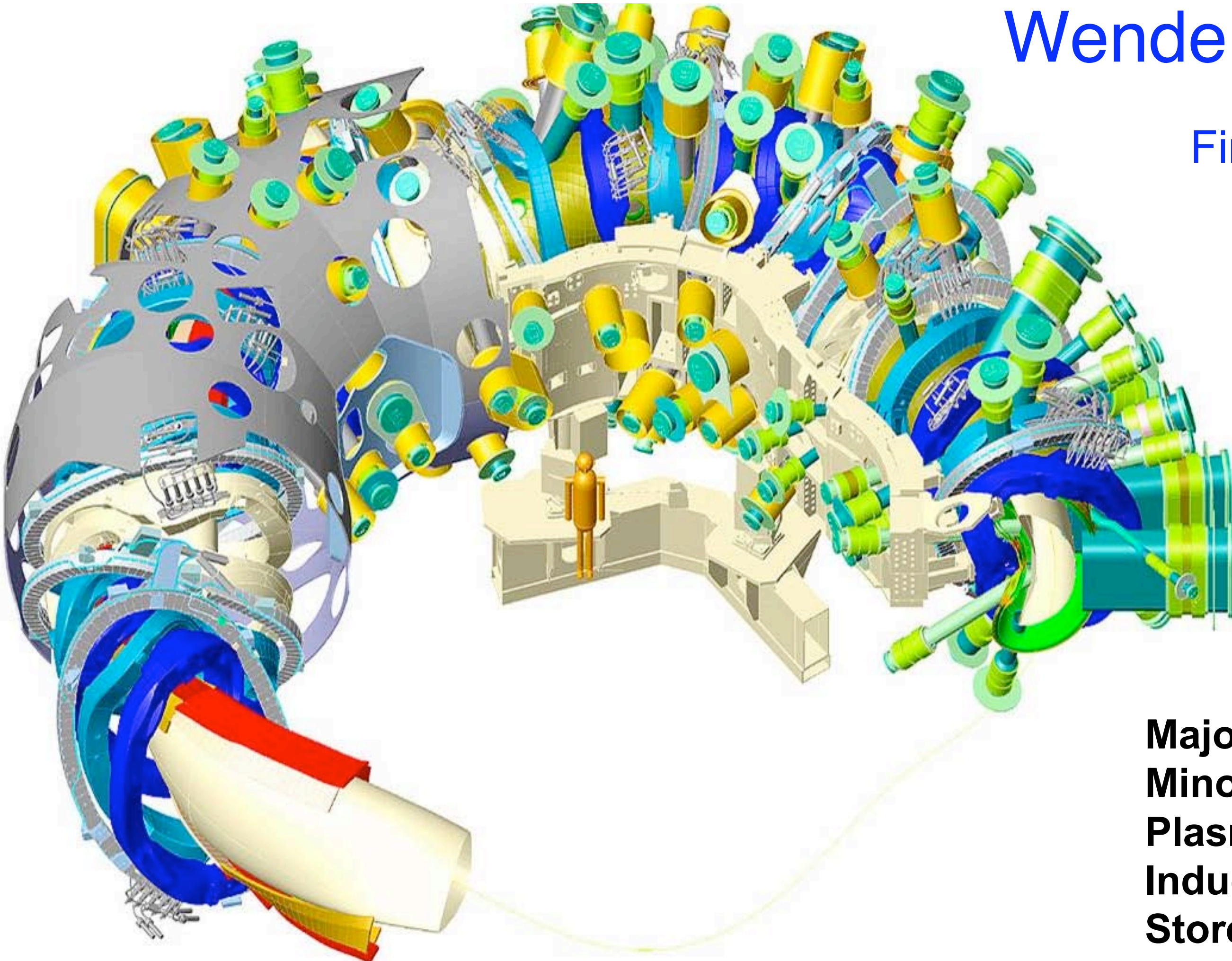




- W7-AS was the first stellarator device based on modular non-planar magnetic field coils
- demonstrated commonality with tokamak physics like access to H-mode confinement regime

An Optimized Stellarator is Under Construction

Max-Planck-Institut für Plasmaphysik



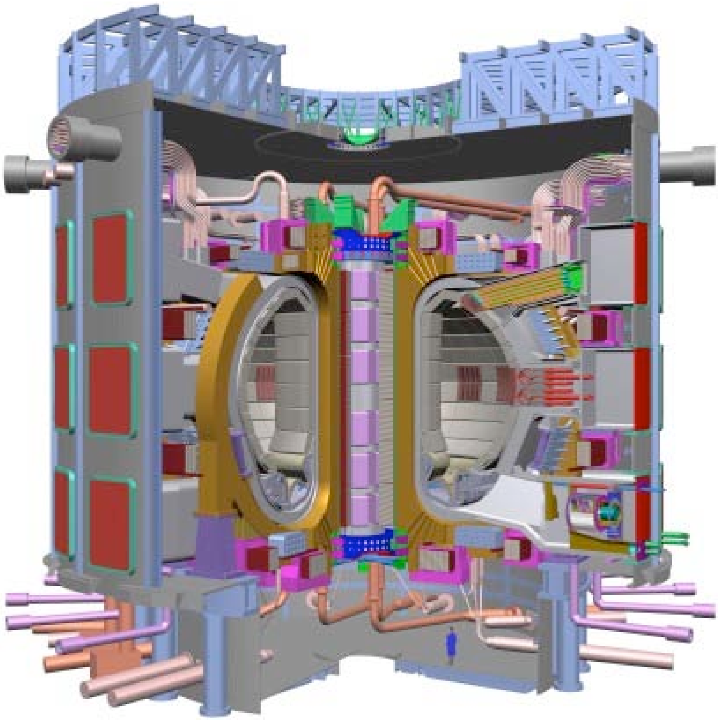
Wendelstein 7-X

First Plasma 2014

Major radius:	**5.5 m**
Minor radius:	**0.53 m**
Plasma volume	**30 m^3**
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.

ITER is Now Underway



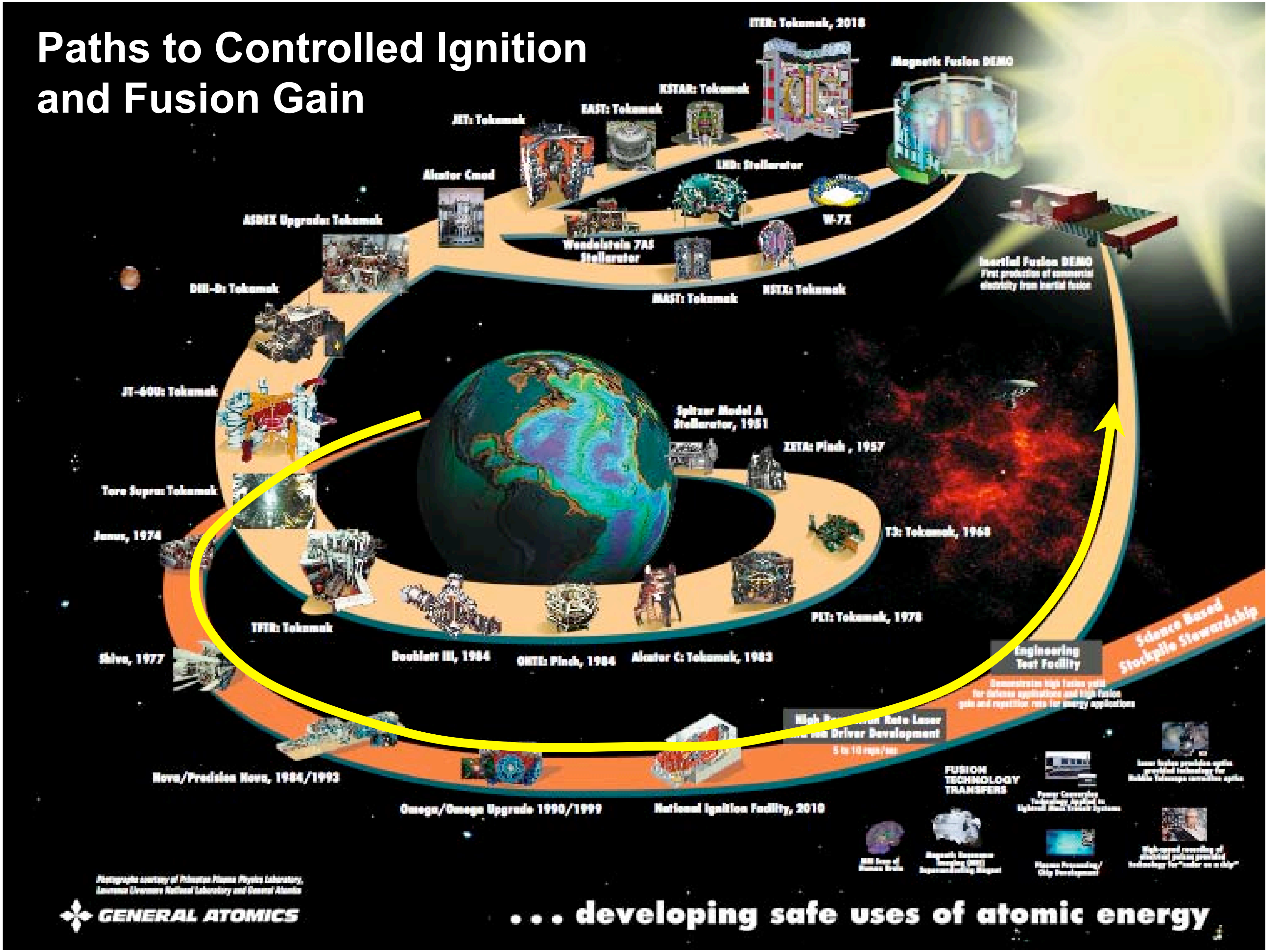
Reactor scale

ITER Site Under Construction

First Plasma planned for 2018

First DT operation planned for ~2022

Paths to Controlled Ignition and Fusion Gain



Inertial Confinement Fusion, Early Days

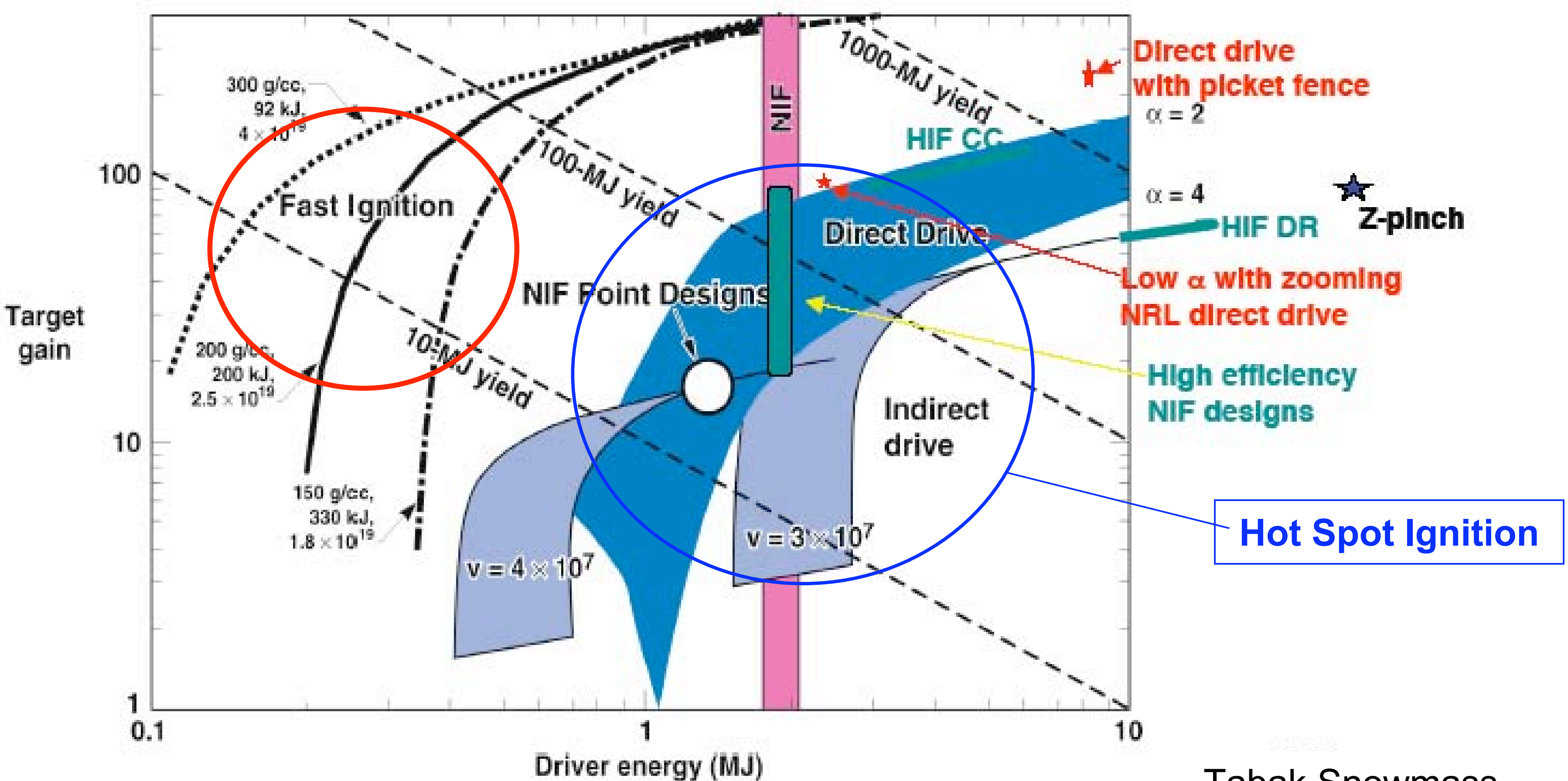
- Radiation compression of DT to produce fusion energy demonstrated in the early 50s in Greenhouse George Cylinder test (and others).
- Invention of the laser in early 60s offered the possibility of a programmable repetitive driver for micro targets. Research continued on intense particle beam drivers 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.

Described in more detail in The Fusion Quest by T. Kenneth Fowler

Construction of NIF/LMJ - ICF Burning Plasmas

- Classified Centurion-Halite nuclear tests in ~1986 reported to have validated compression modeling
- Many aspects of US ICF declassified in Nov 1994, allowing target designs to be discussed.
- Omega project reports gain of ~ 1% 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.
- Test Ban Treaty and resulting Stockpile Stewardship Program provided justification for the construction of the National Ignition Facility (NIF) in 1998. Construction now scheduled to be completed in 2009, with first ignition experiments in 2010.

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



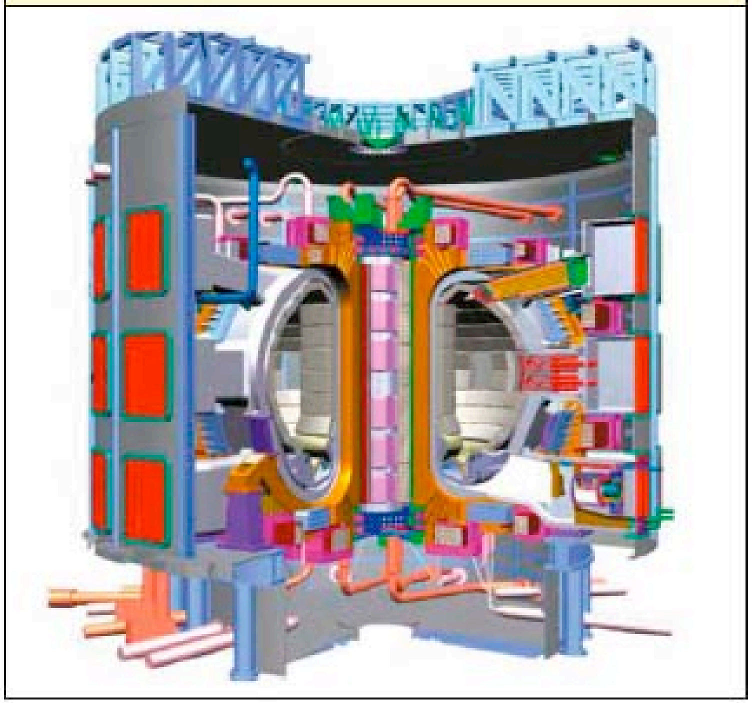
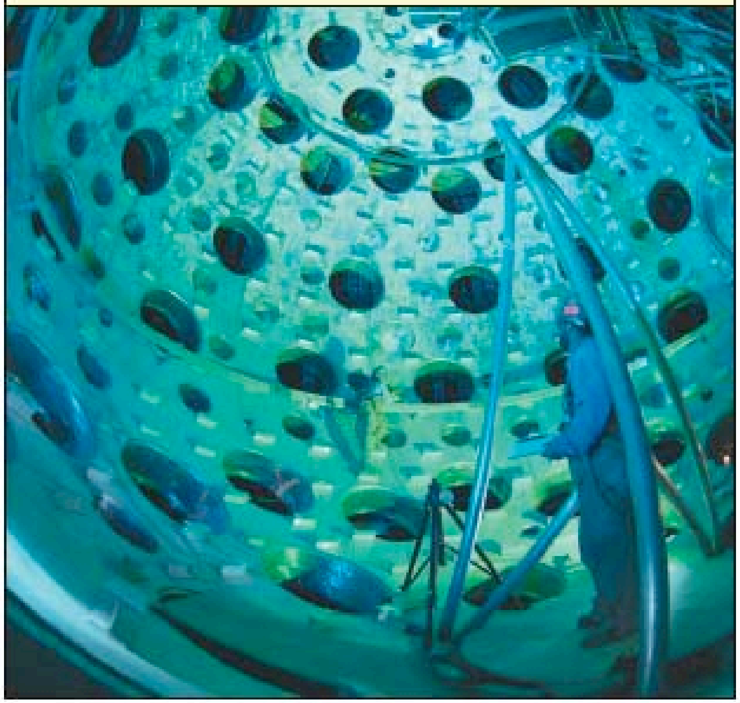
Tabak Snowmass

FI Expt's -
Omega, FIREX,
HIPER

Some Overall Highlights

- A strong scientific basis has been established for fusion.
- Diagnostics and Plasma Technology (Aux heating, CD, pellet inj) enabled progress.
- 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	Inertial Fusion Energy
	

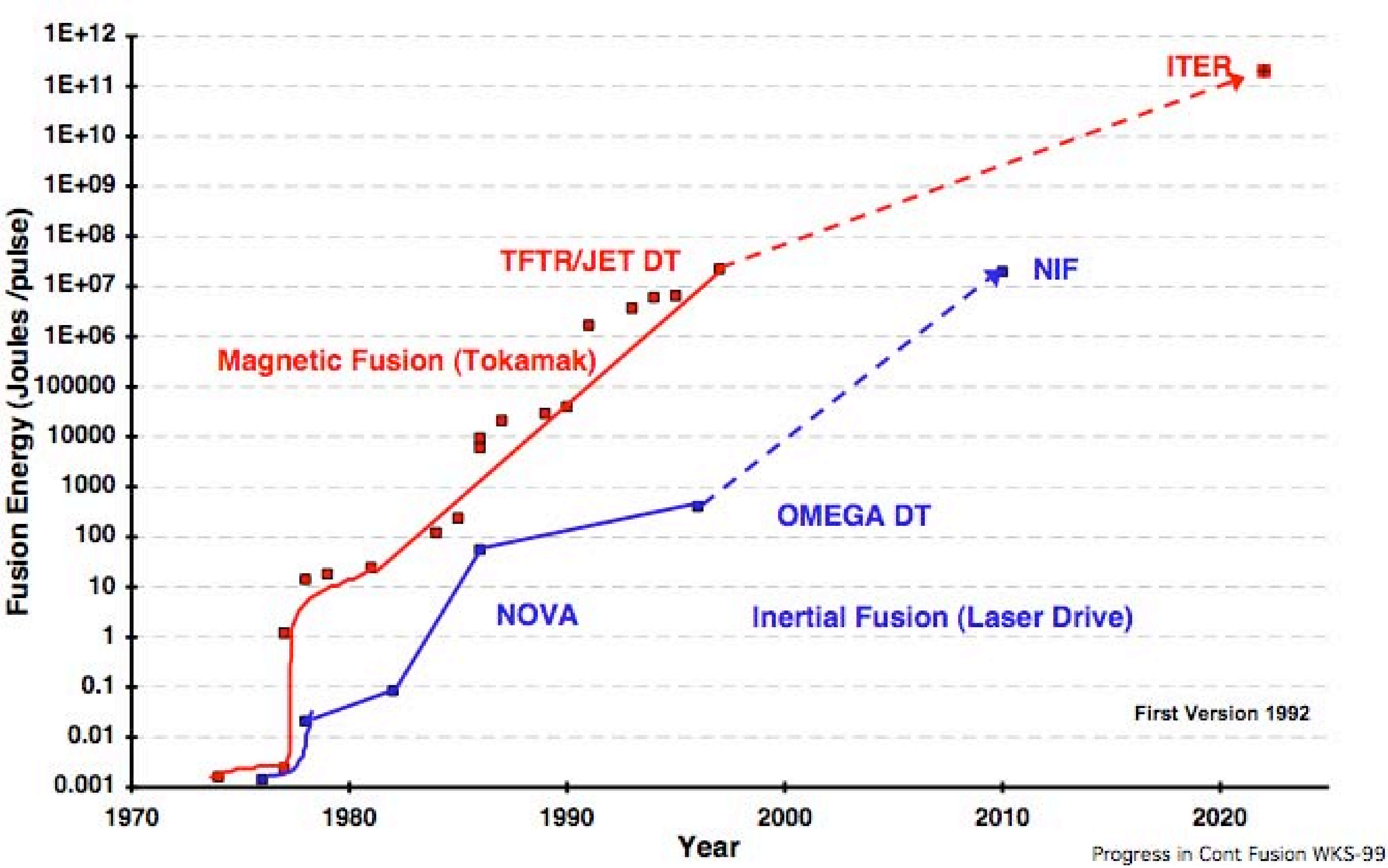
ITER

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




The Highlight for the next 50 years.
Fusion energy will begin powering the world.