The Prospects of Nuclear Fusion

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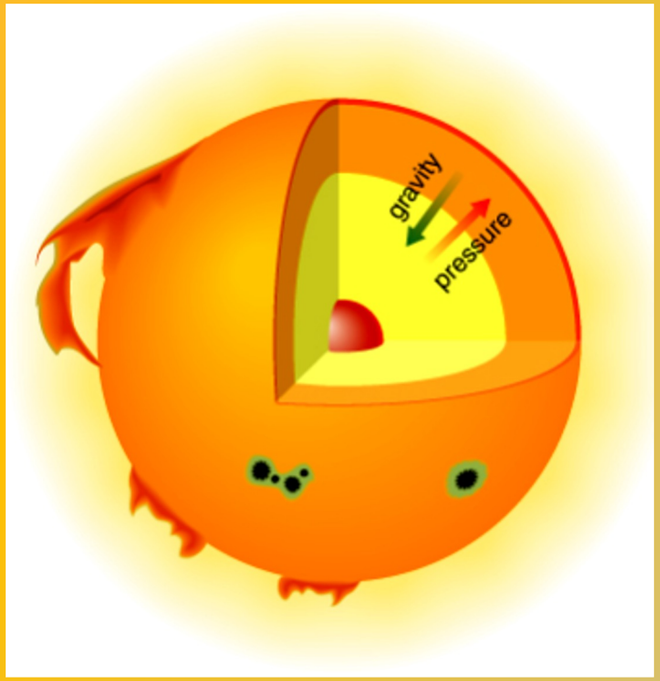
Institute for Plasma Research

Tamilnadu Science Forum

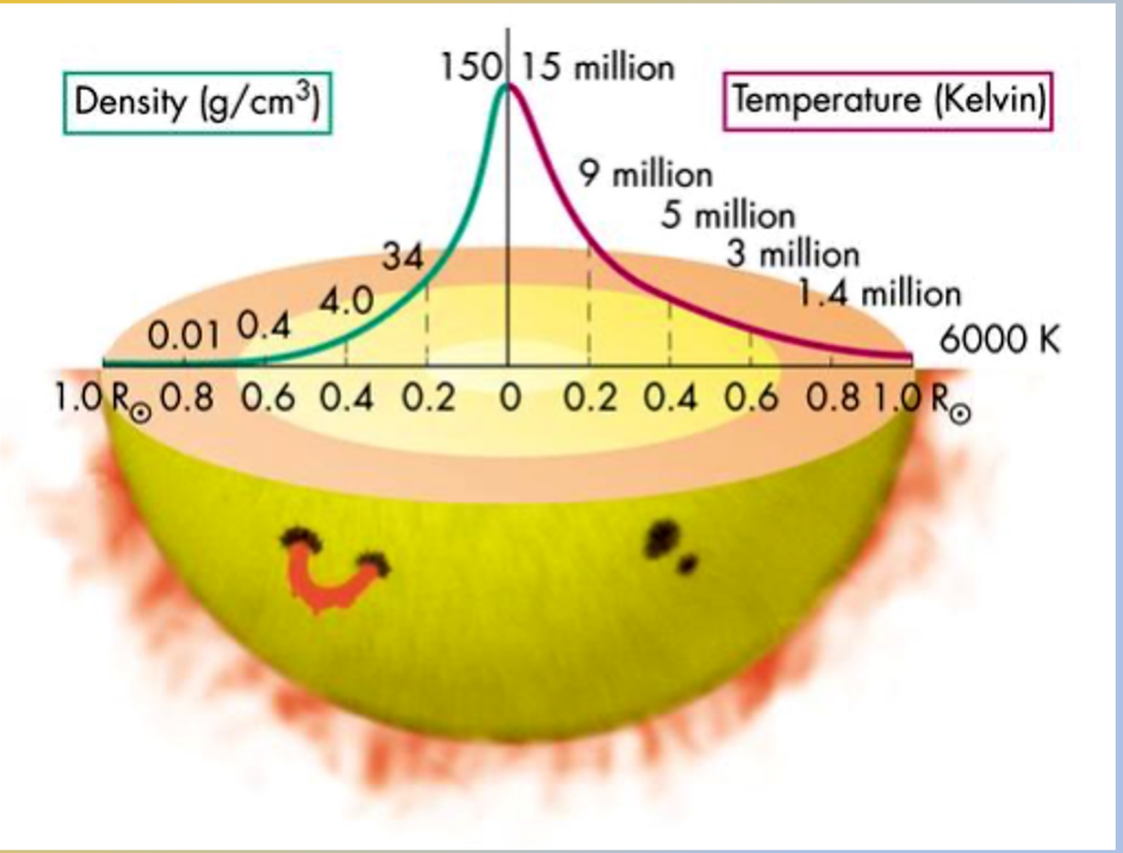
10 April 2022

Stellar Equilibrium

Temperature 15 Million Deg
Pressure 340 Billion Atm



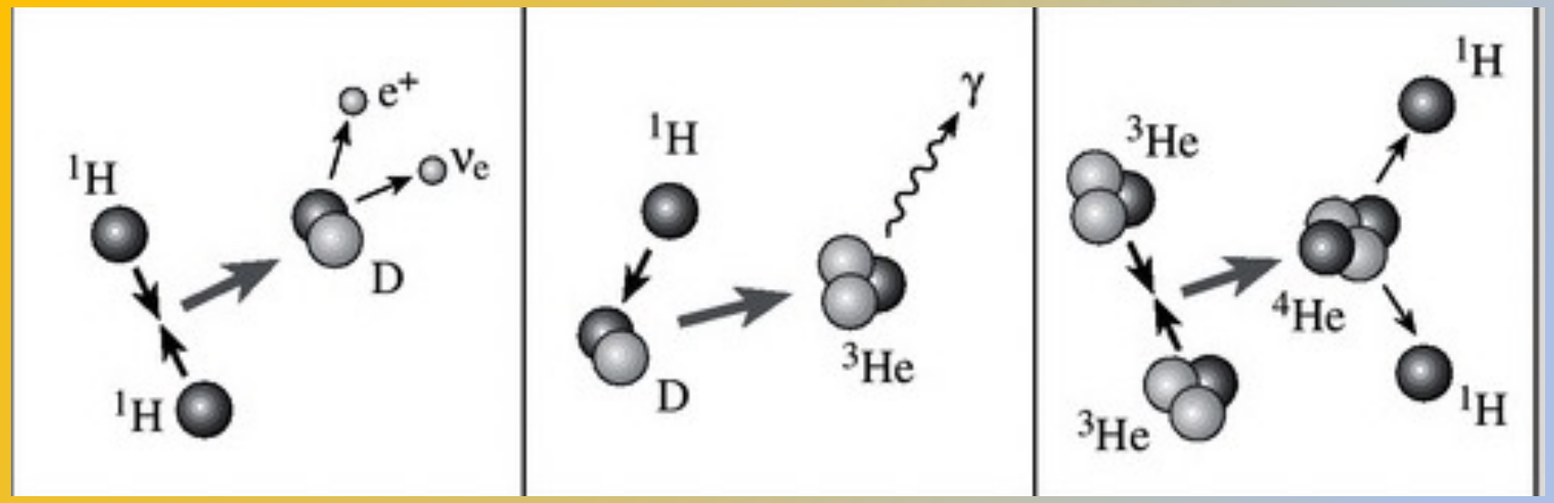
Pressure (from heat caused by nuclear reactions) balances the gravitational pull toward the Sun's center.



What Makes the Sun Shine?

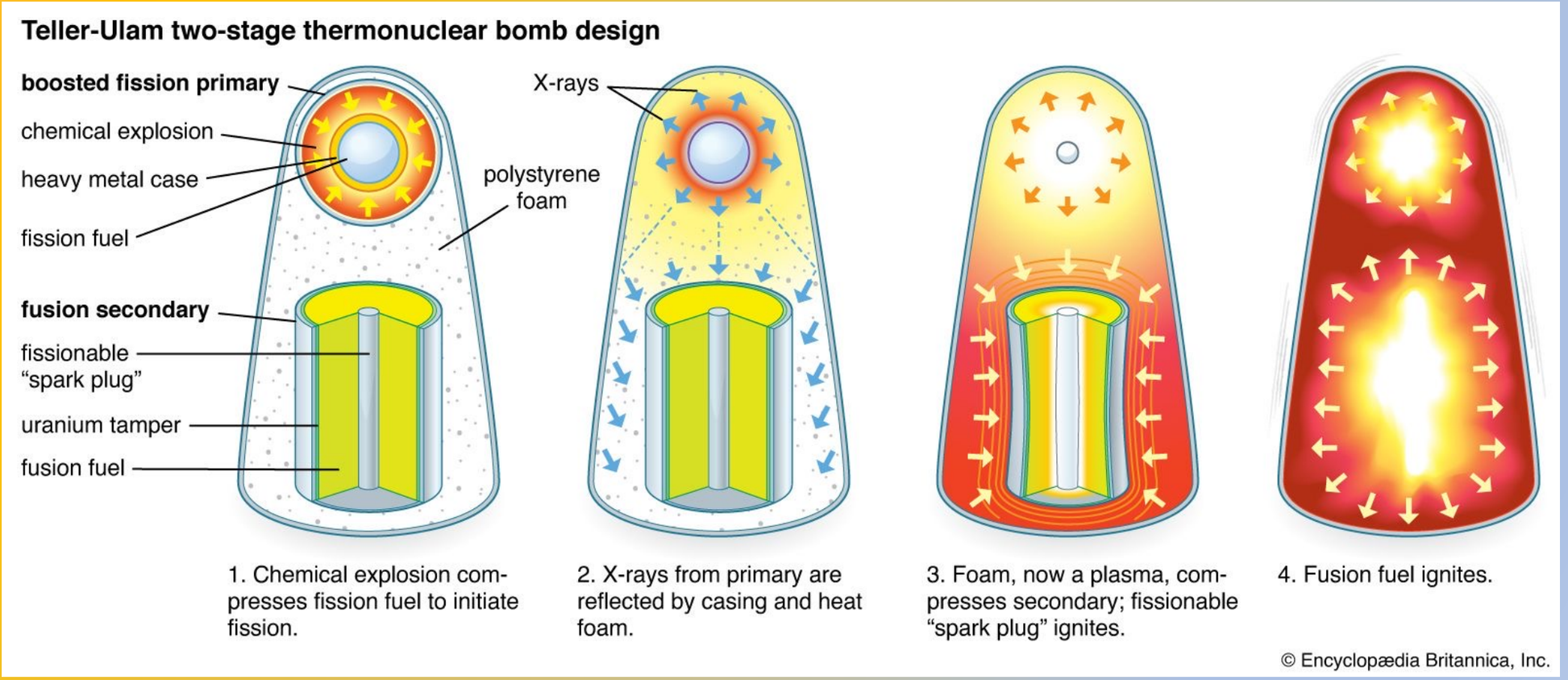
1926, **Arthur Eddington**

Stars draw their energy from the conversion of hydrogen into helium by thermonuclear fusion.

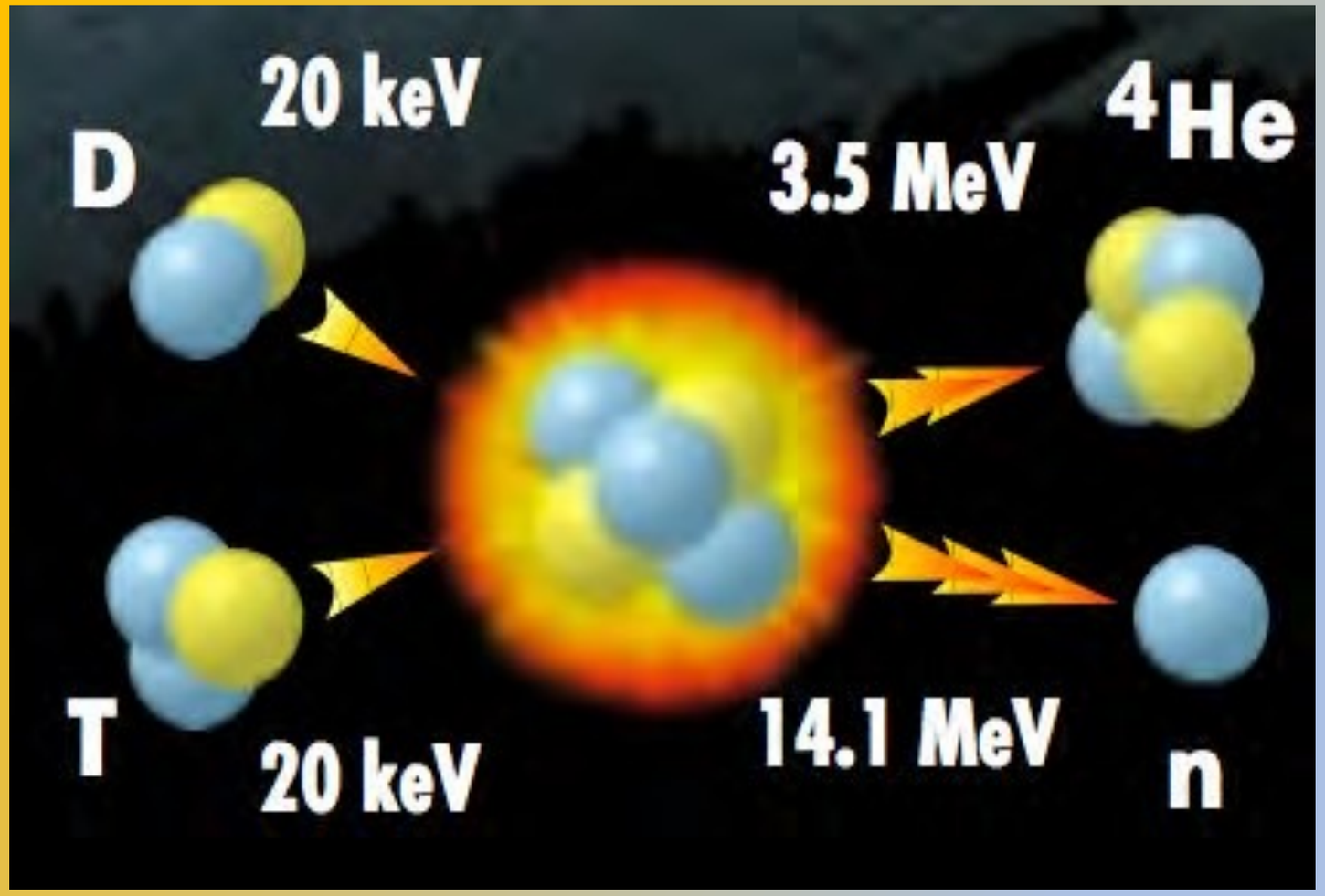


Hans Bethe: P**roton-Proton chain** 1939

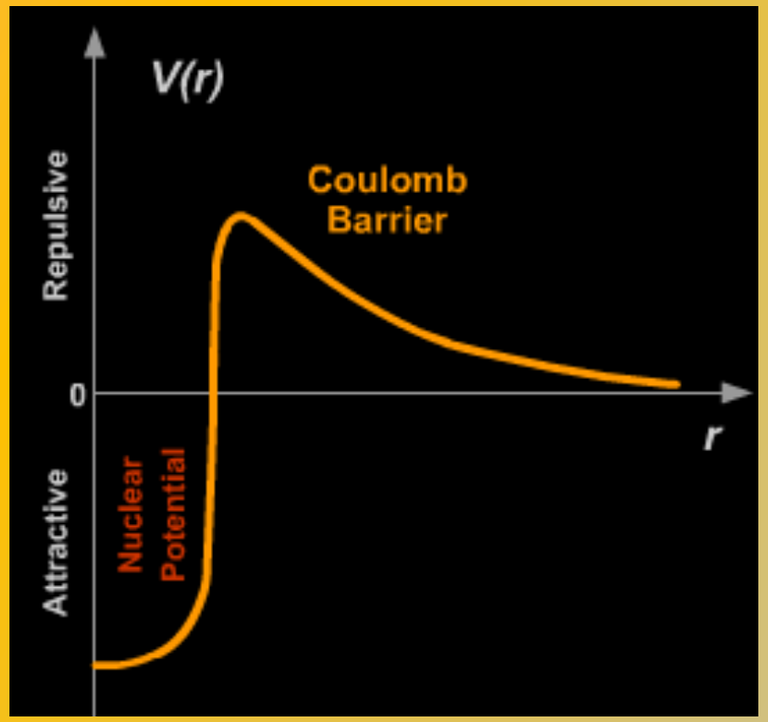
Fusion on Earth?
The Extreme Temperature-Pressure conditions are transiently created in the H Bomb

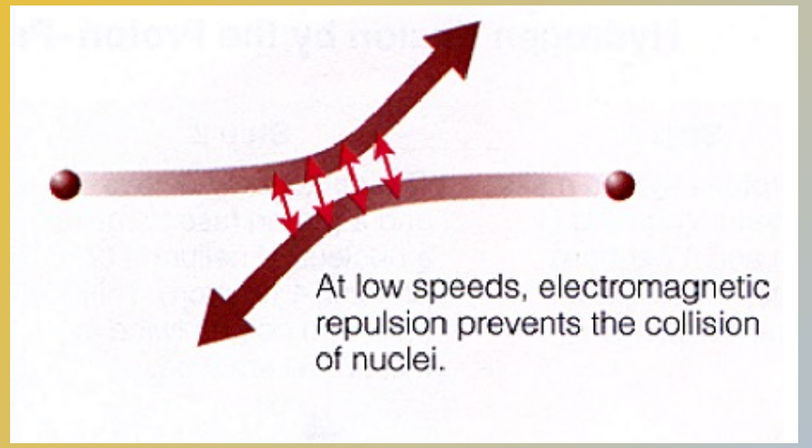


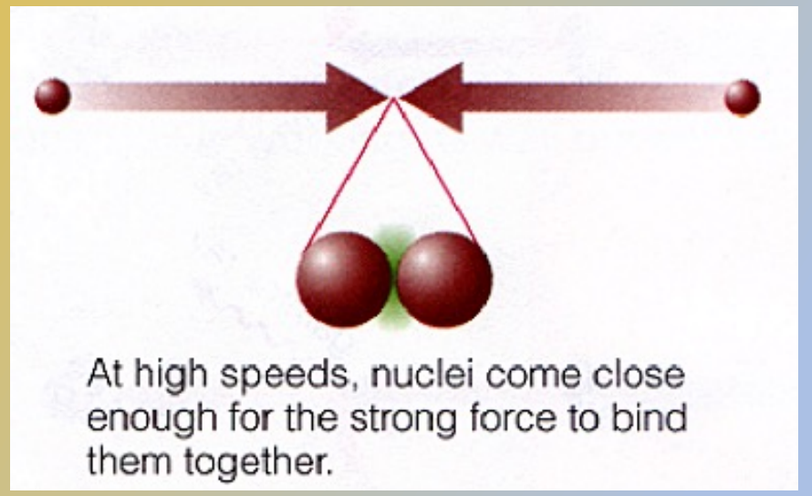
Deuterium and Tritium nuclei fuse together to form Helium and release energy
in the form of 14 MeV Neutrons



Why Nuclear Fusion is difficult to achieve!







Coulomb repulsion of positive nuclei

Bring them close to 10^{-15}m
Nuclear Force Takes Over
At speeds corresponding to 100 Million Degrees, nuclei can overcome the Coulomb repulsion.

Approach I

Inertial Confinement Fusion (ICF)

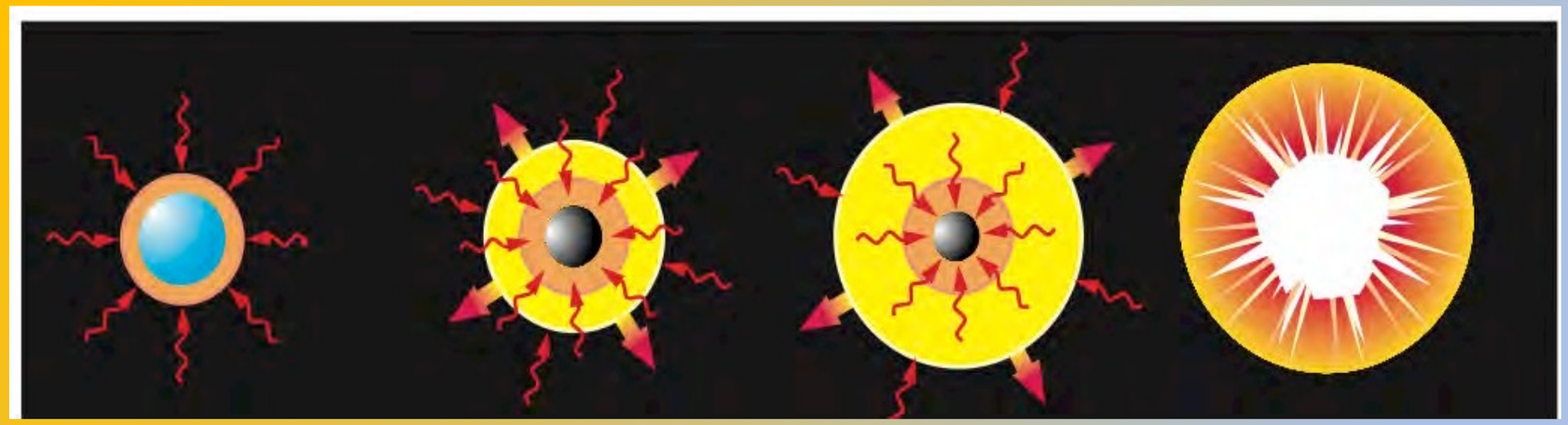
Use powerful lasers or particle beams to compress and heat a tiny DT pellet

Approach II

Magnetic Confinement Fusion (MCF)

Use Intense magnetic field to trap and confine a plasma heated to 100 Million deg

Approach I : Inertial Fusion



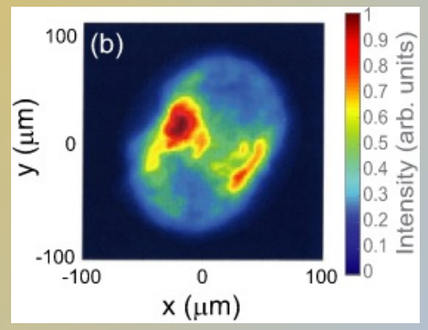
Heating of the surface of mm sized pellets

Ablation of outer skin leads to compression

The core heats up by compression

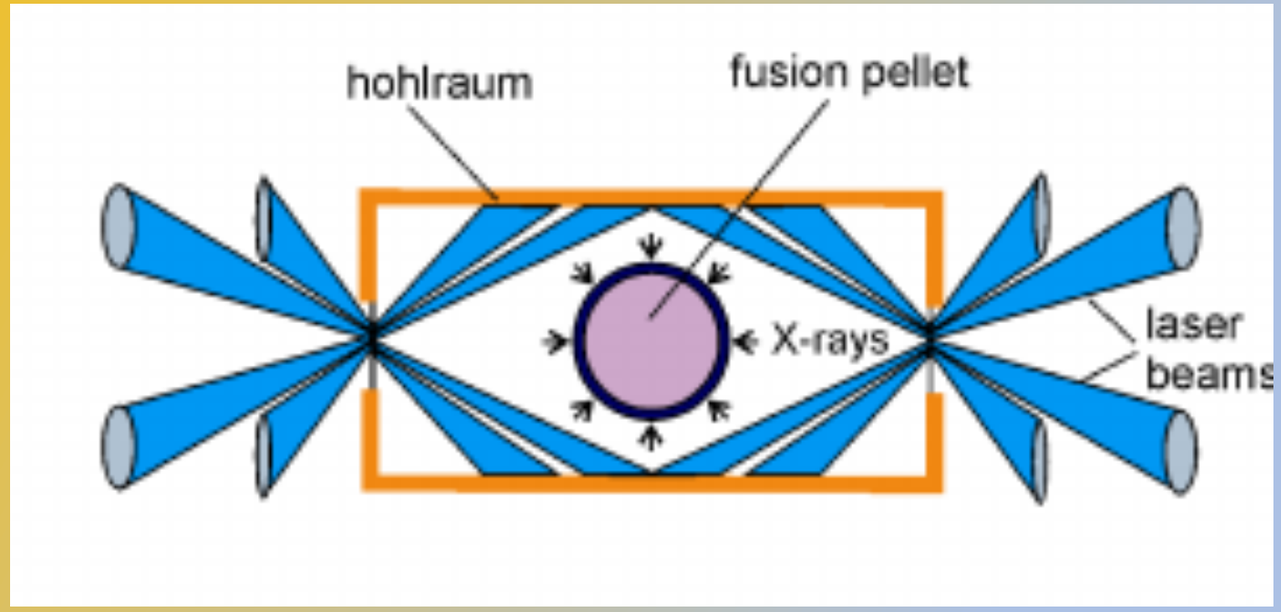
Fusion

Direct heating leads to non-spherical compression/break-up

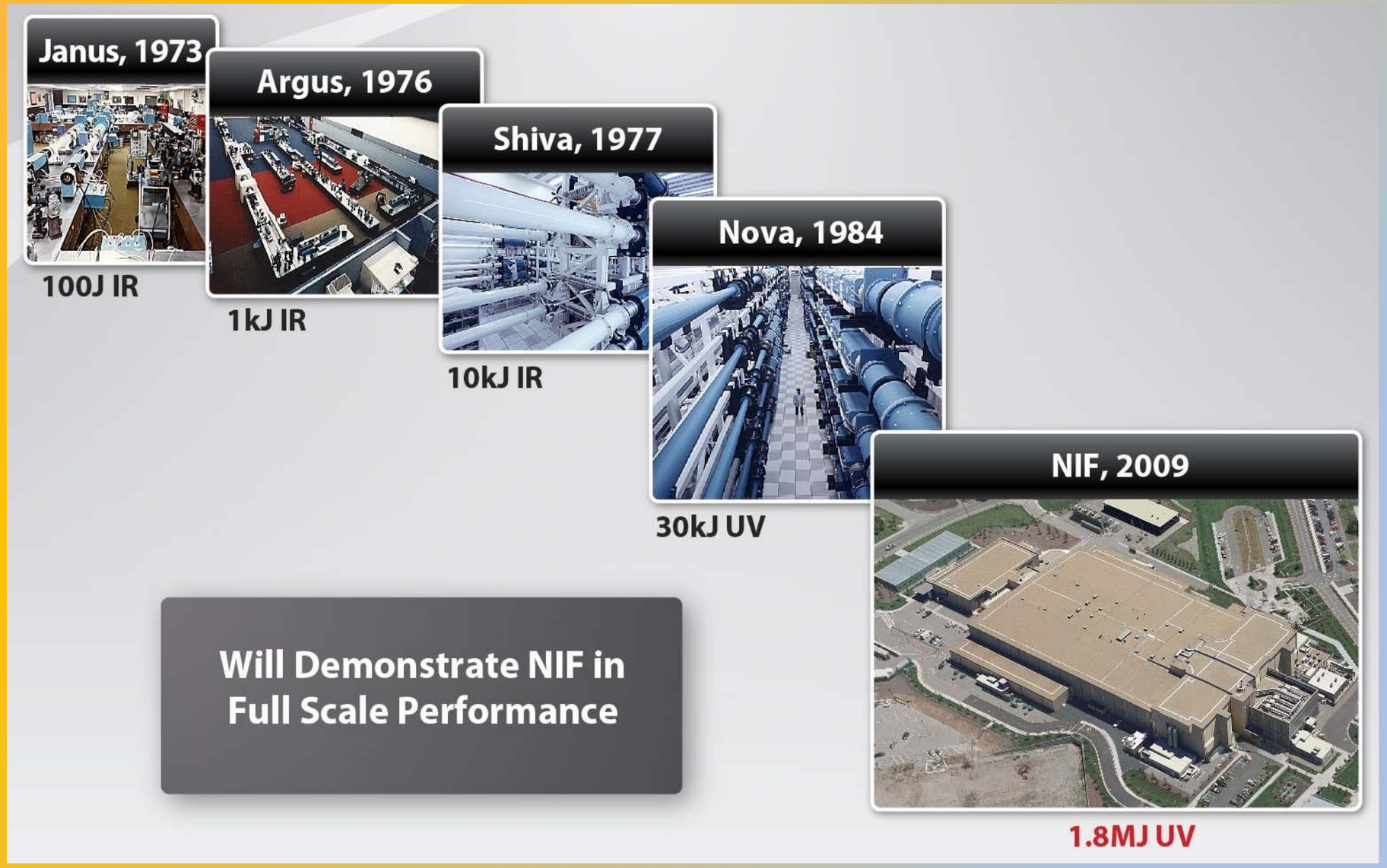


JOHN NUCKOLLS, LOWELL WOOD, ALBERT THIESSEN & GEORGE ZIMMERMAN

Nature
volume 239, pages 139–142 (1972)



Indirect Heating



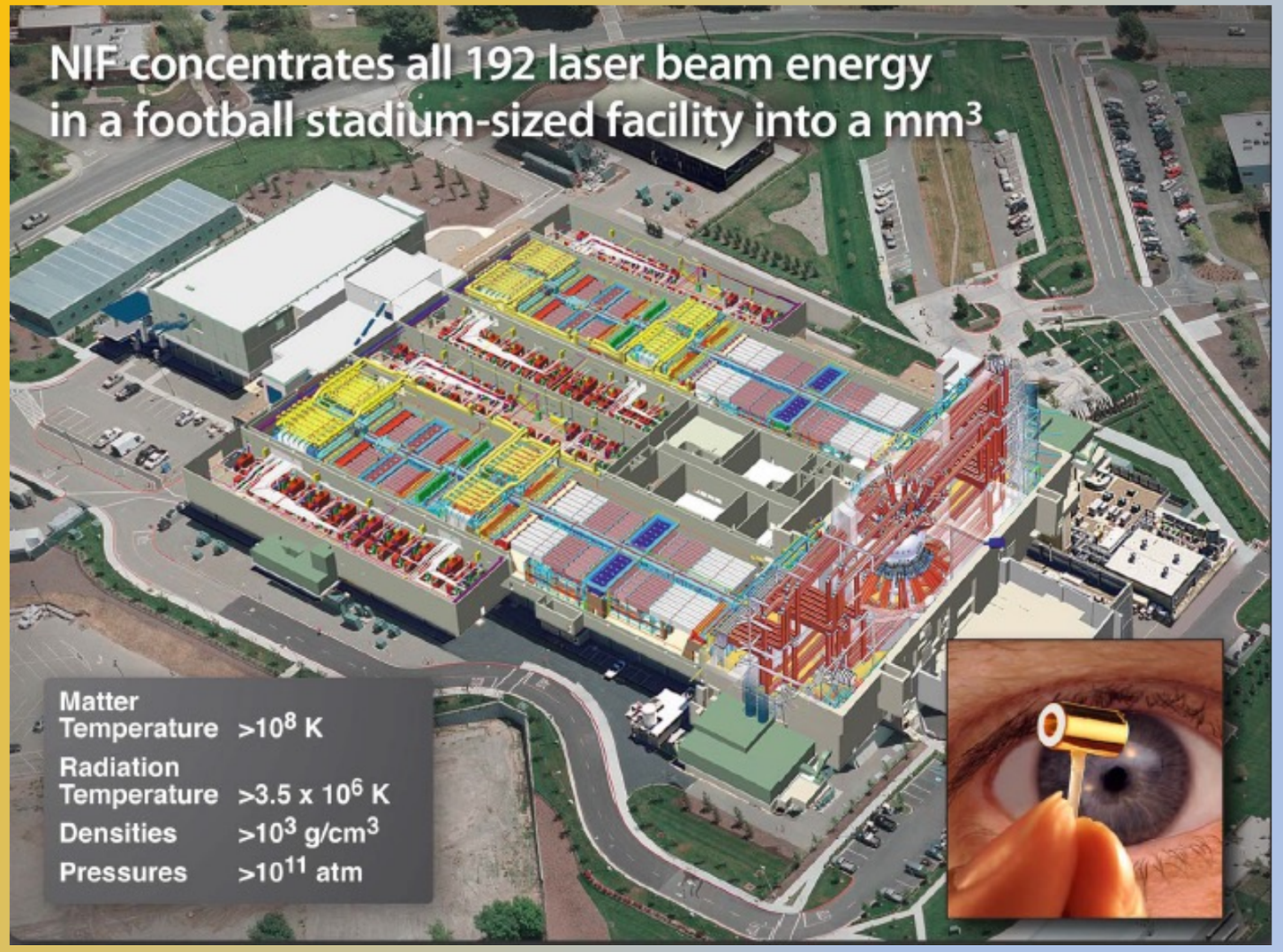
The NIF facility is the culmination of many decades of US leadership and investment in this field

National Ignition Facility

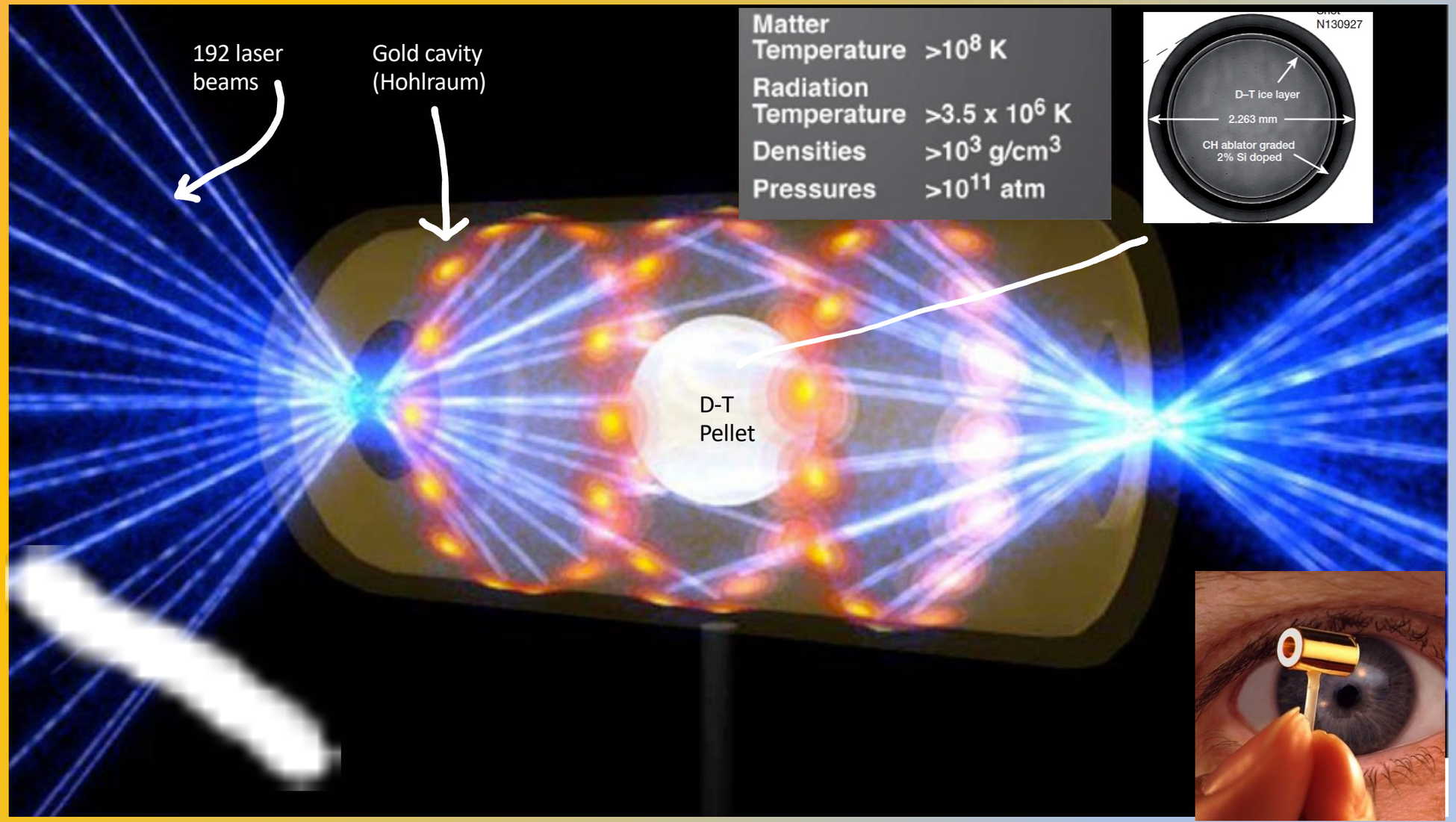
192 Beams

10^{15} WATTS

Lawrence Livermore National Laboratory



Ignition!


192 laser beams
Gold cavity (Hohlraum)
Matter Temperature >10^8 K
Radiation Temperature >3.5 x 10^6 K
Densities >10^3 g/cm^3
Pressures >10^11 atm
N130927
D–T ice layer
2.263 mm
CH ablator graded 2% Si doped
D-T Pellet

On Aug. 8, 2021, researchers at Lawrence Livermore National Laboratory (LLNL) attained a historic breakthrough in fusion

National Ignition Facility (NIF) produced more than 1.3 million joules of fusion energy.

Many more steps before a reactor

Approach II: Magnetic Confinement Fusion

- Matter completely ionized = **Plasma**
- Thermalized plasma T ~ 10,000 eV ~ 100,000,000 K
- Far out of thermodynamic equilibrium in laboratory environment
- Plasma loses heat $\rightarrow$ needs energy confinement.
- Lawson Criterion: $NT\tau_E > 10^{21}$ **(keV m^{-3} s) with T between 10 to 20 keV**

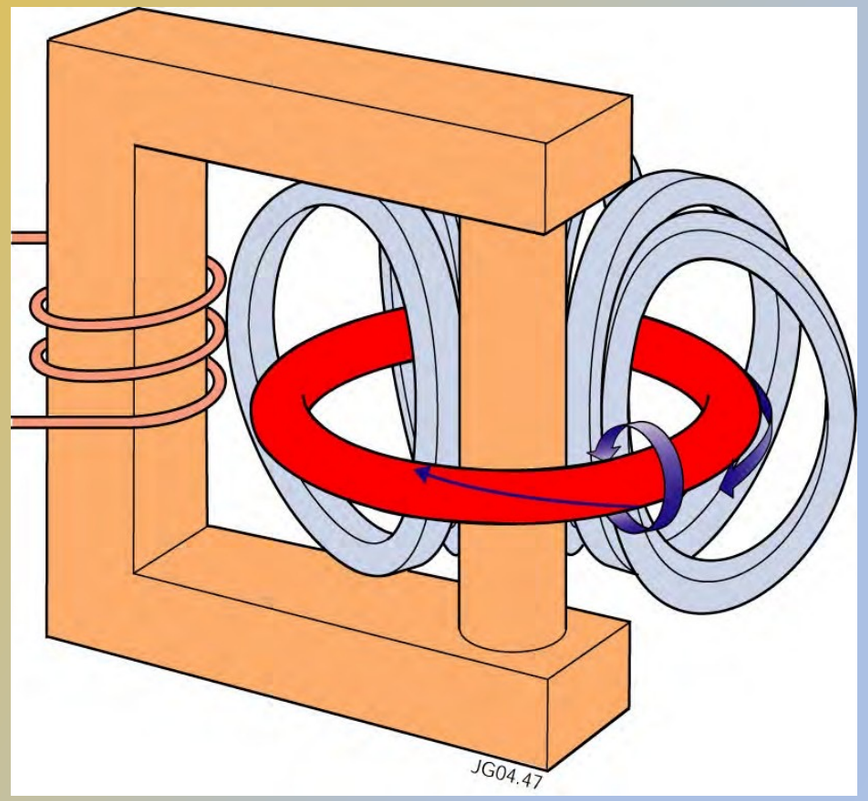
Tokamak is the most successful magnetic trap

toroidalnaya **ka**mera,
s**ma**gnitnami
katushkami

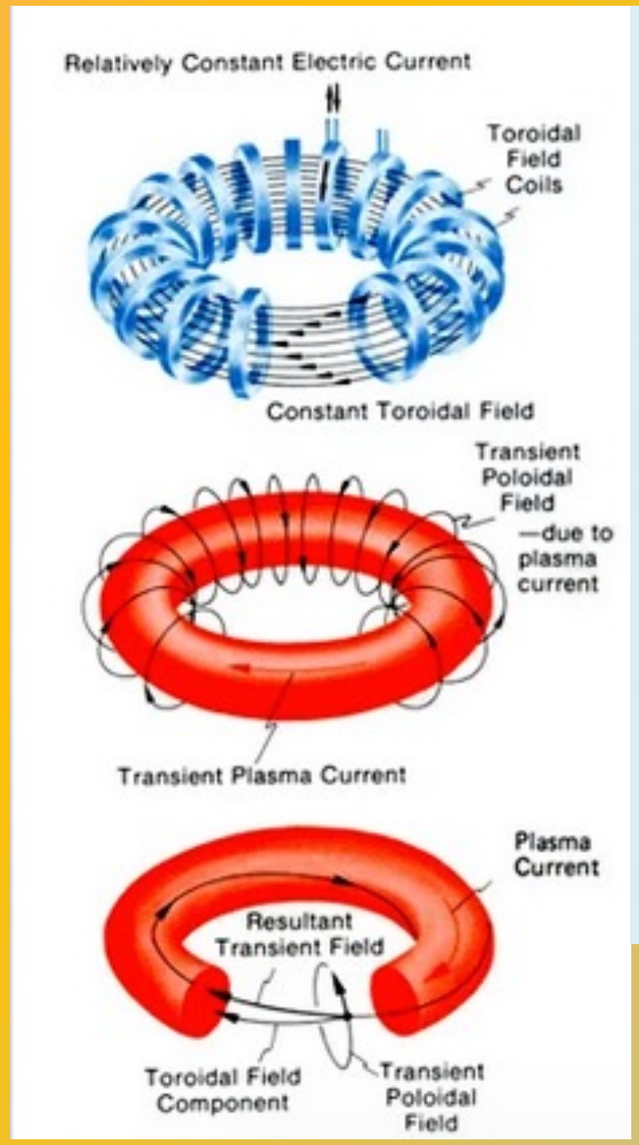
(“**toroidal chamber**” with “**magnetic coils**”)

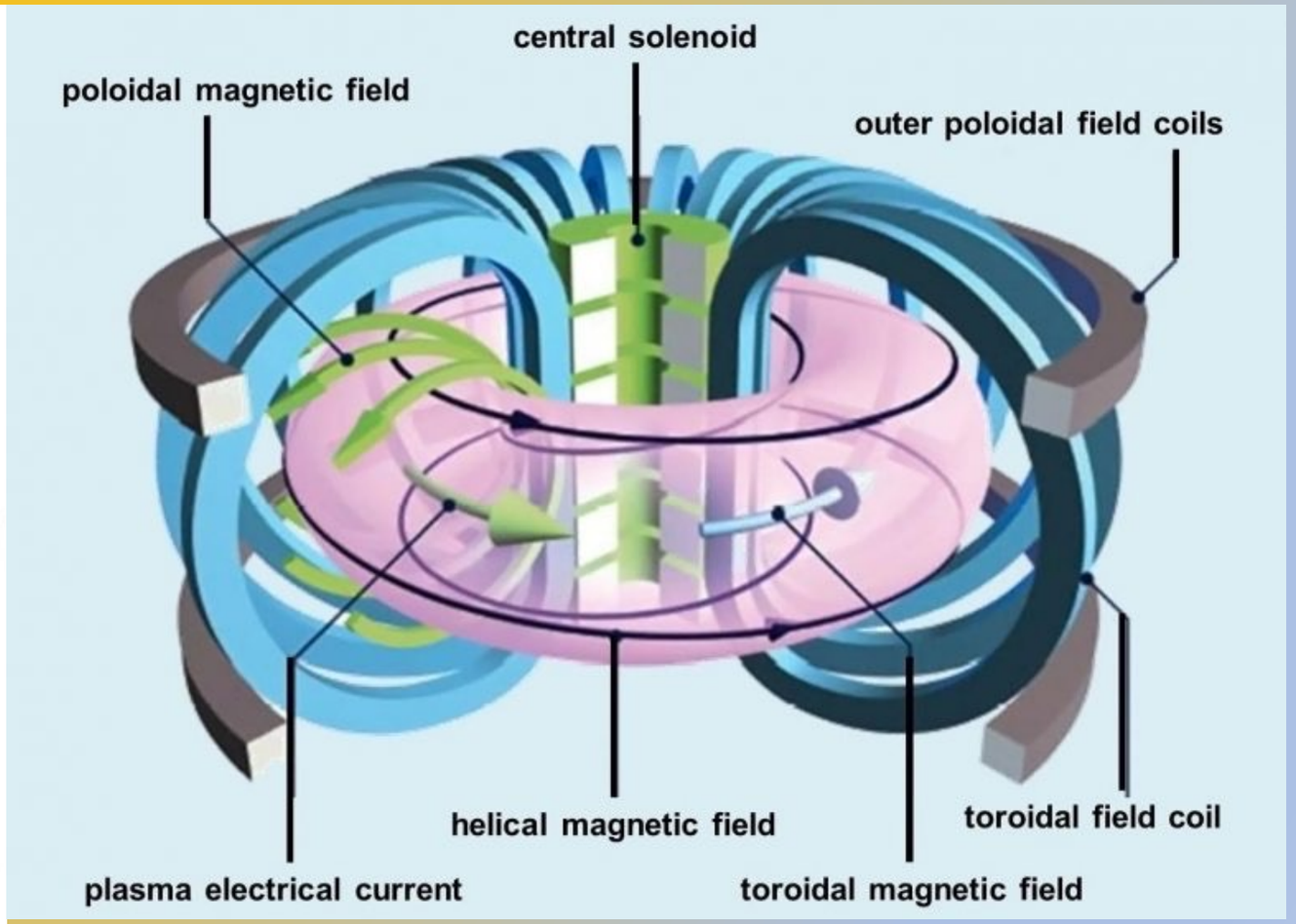
Andrei Sacharov and Igor Tamm at the Kurchatov Institute in Moscow in 1950

Transformer



Magnetic Confinement





PLASMA HEATING

Ohmic Heating

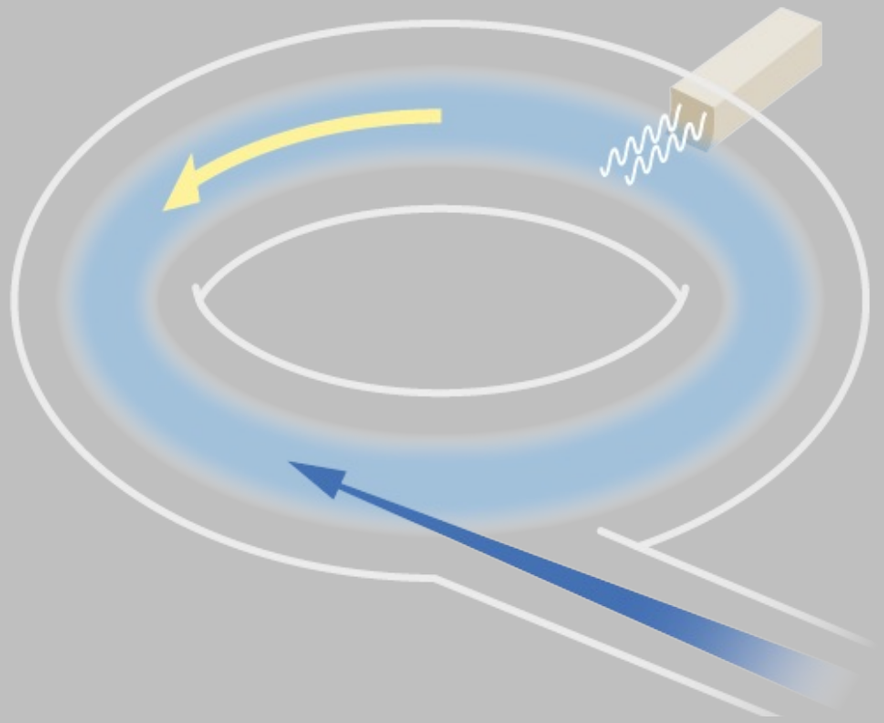
I^2R

Produced by plasma current

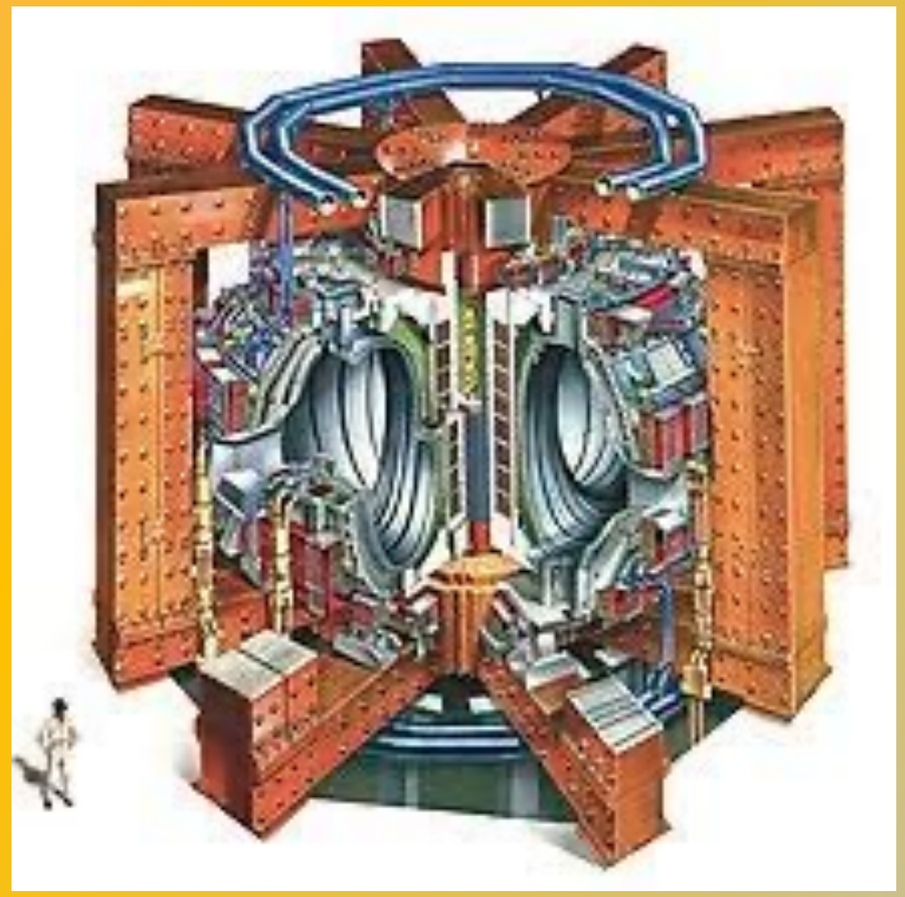
No resistive heating since hot plasma is a good conductor

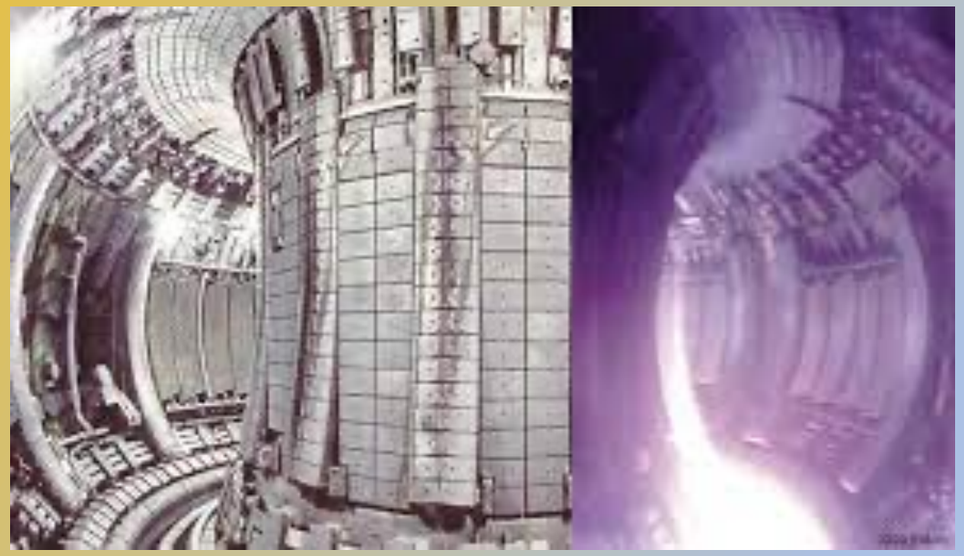
Neutral beam injection
- Injection of fast particles
- Collisions with plasma particles
- Energy transferred to plasma

Wave heating
- Injection of high frequency waves
- Wave – plasma resonance
- Energy transferred to plasma



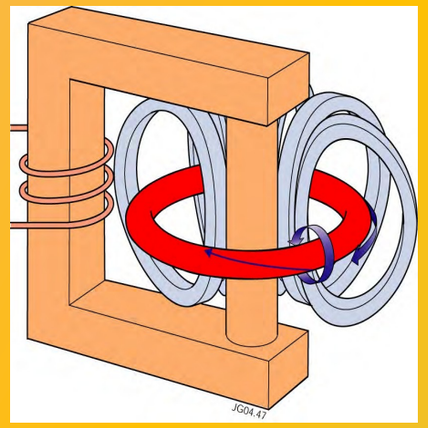
Joint European Torus

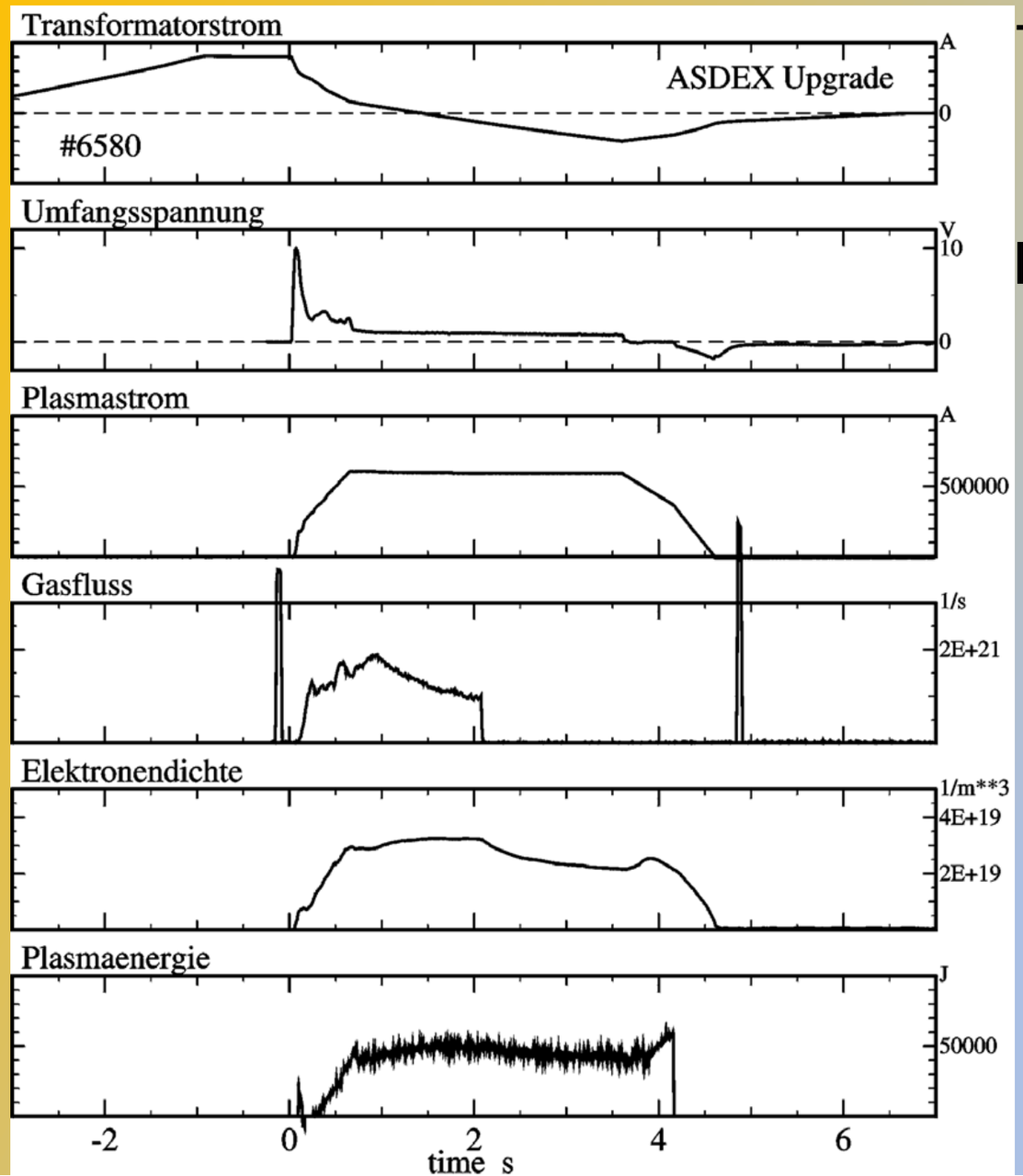




Operating at Culham
Lab in Oxford
Since 1983

Typical evolution of a tokamak discharge





Transformer Current

loop voltage

Plasma current

Gas

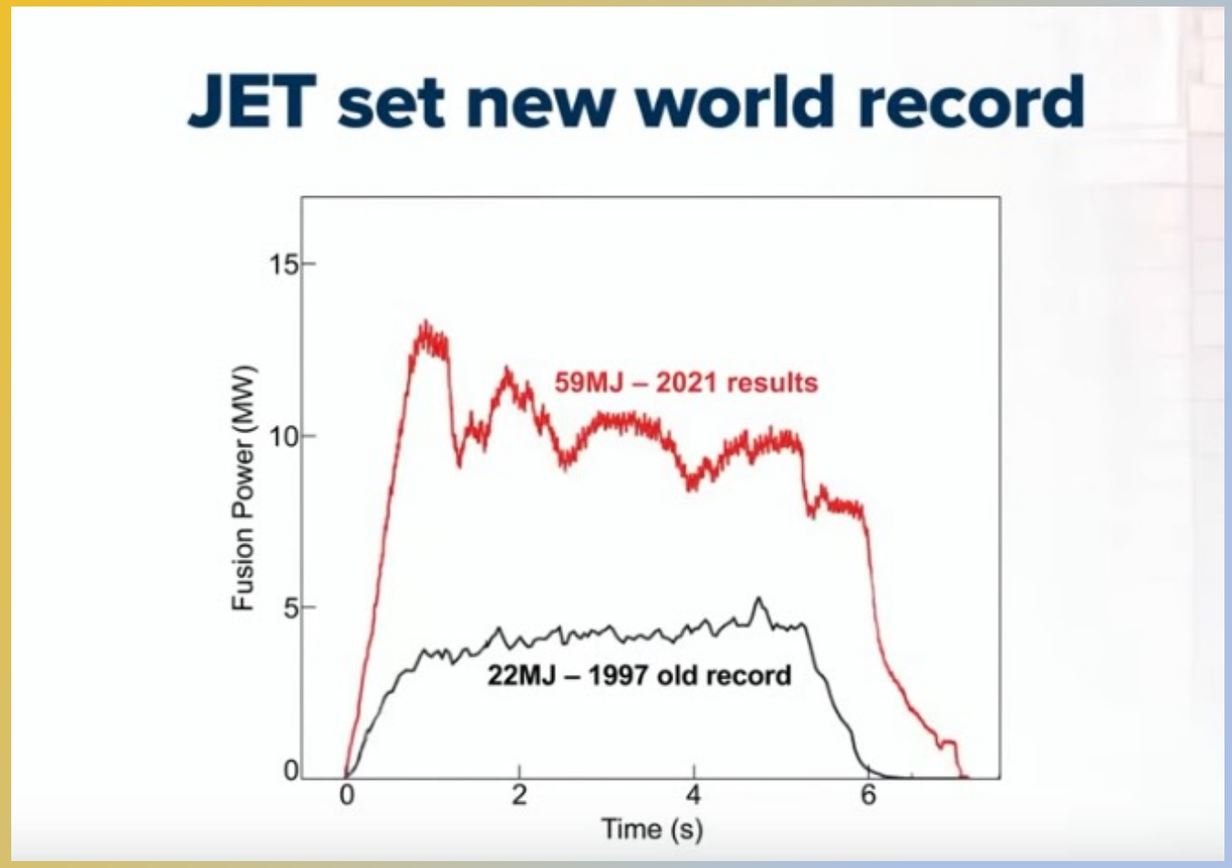
Electron density

Plasma stored energy

In an experiment on 21 December 2021, JET produced 59 megajoules of energy over a fusion ‘pulse’ of five seconds.

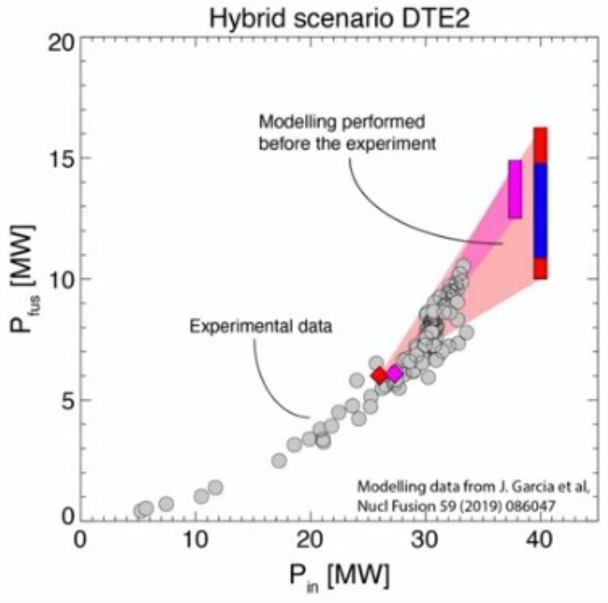
40 MW input power.

More than double the 21.7 megajoules released in 1997 over around four seconds. Q = 0.33



EUROfusion

4. D-T results confirm modelling predictions



- D-T fusion power achieved matches the predictions
- New JET data are crucial to predict fusion in ITER and future machines
- Wealth of new JET data to validate the models and extrapolate to ITER and beyond

The Next Step: ITER

JET		ITER	
Size	~8 m	Size	~17 m
Magnetic Field	<4 T	Magnetic Field	5.3 T
Current	<4 MA	Current	<15 MA

ITER: A Brief History

Geneva Summit in 1985:
Gorbachev - Reagan agreement

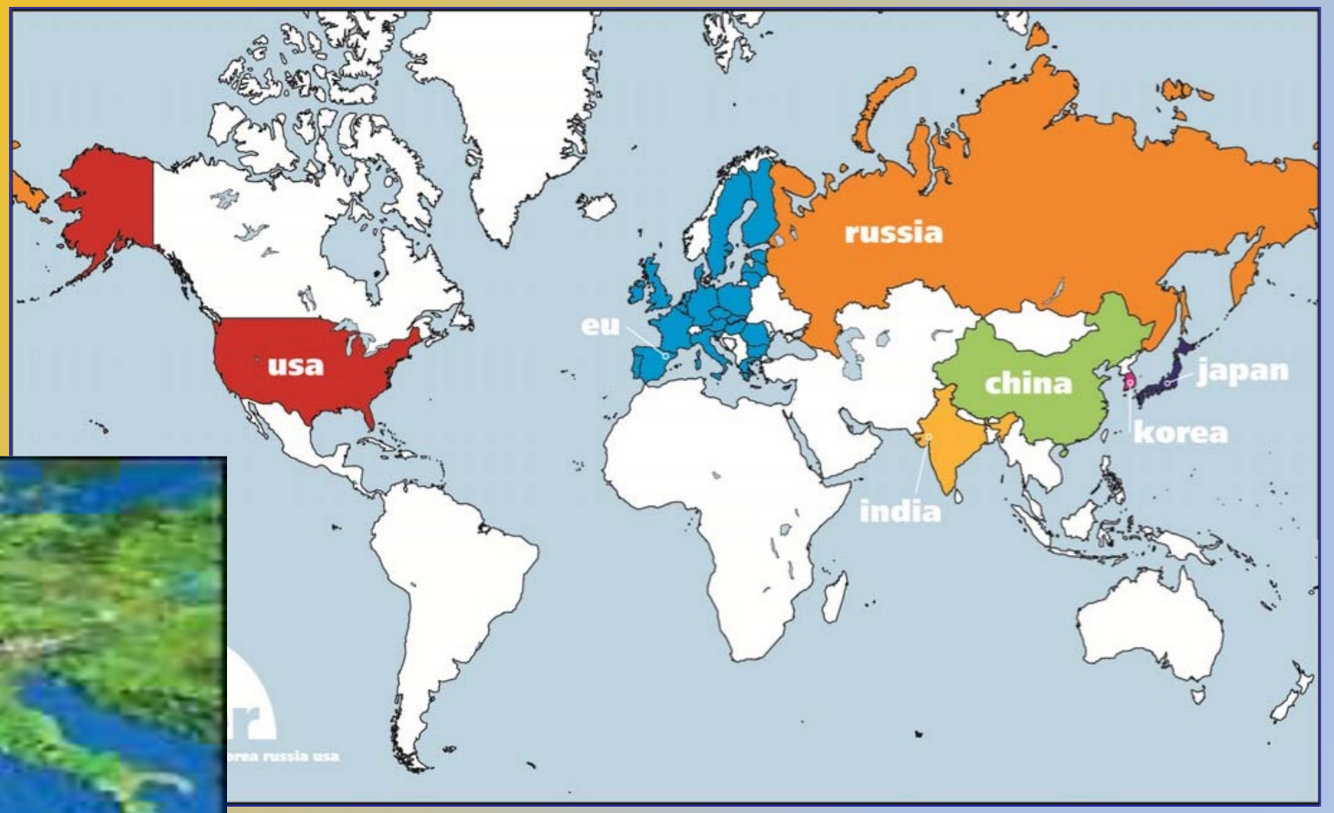
International project to develop fusion energy for peaceful purposes.

INTOR DESIGN
Toronto 2001

ITER Agreement
Signed 2006

The ITER Project

- Demonstrate the scientific and technological feasibility of fusion power for peaceful purposes.
- International cooperation between countries with more than 50% of the world's population.



Cadarache
South of France

The ITER Tokamak

Cryostat
24 m high x 28 m dia

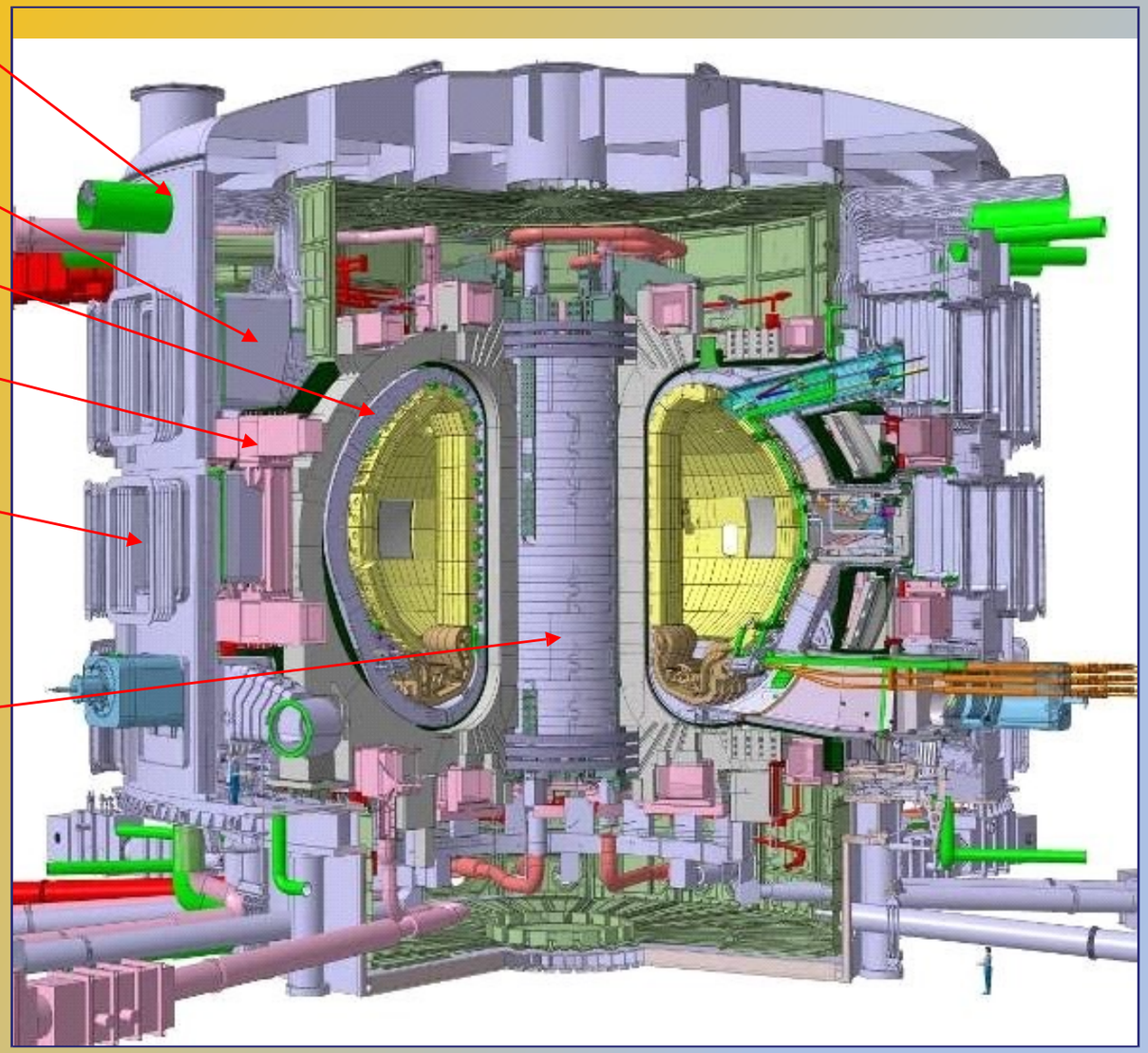
Toroidal Field Coil
Nb_3Sn, 18, wedged

Vacuum Vessel
9 sectors

Poloidal Field Coil
Nb-Ti, 6

Port Plug
heating/current drive, test blankets
limiters/RH
diagnostics

Central Solenoid
Nb_3Sn, 6 modules

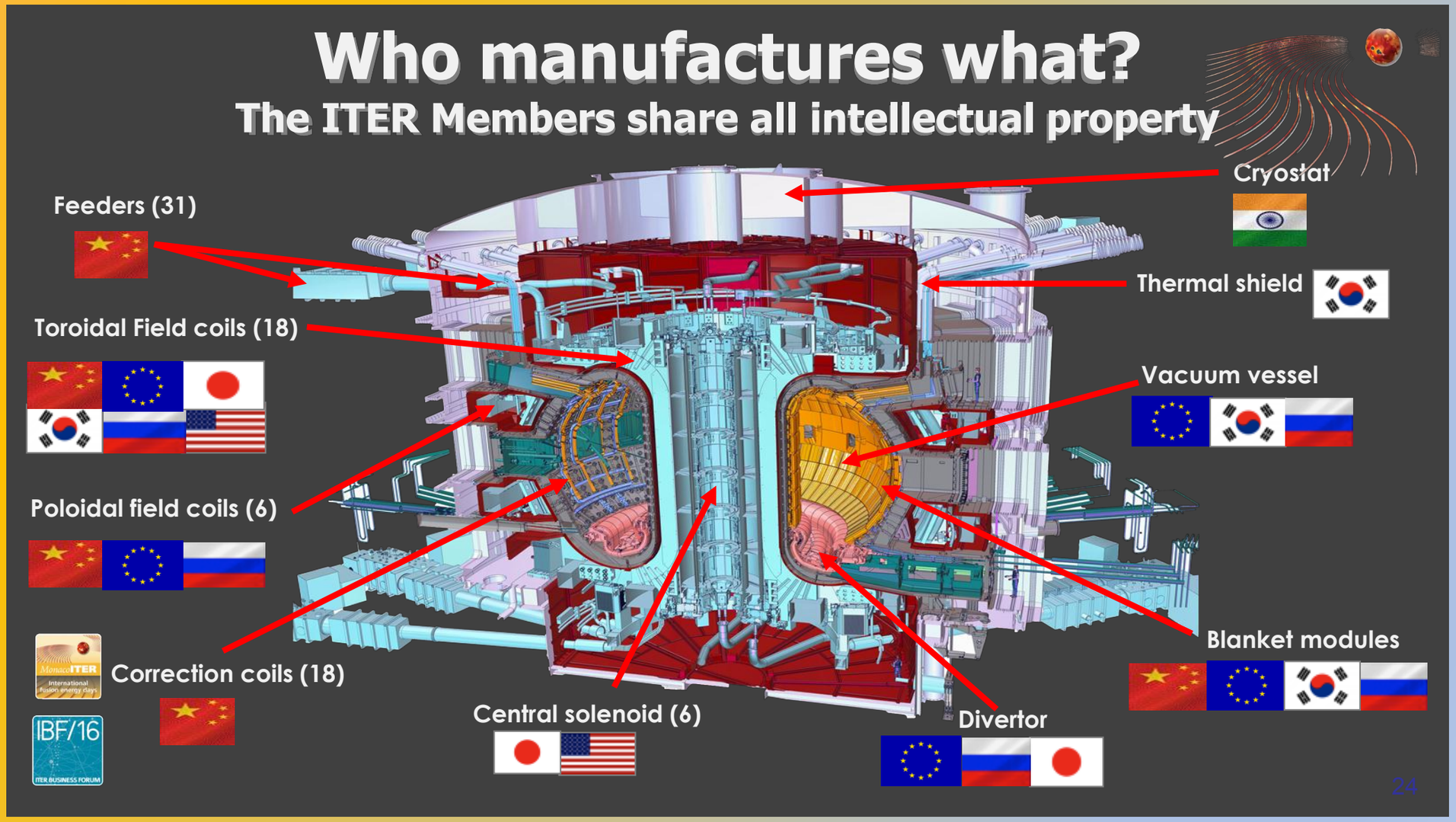


Man standing

- **Weight ~23000 t**

Who manufactures what?

The ITER Members share all intellectual property



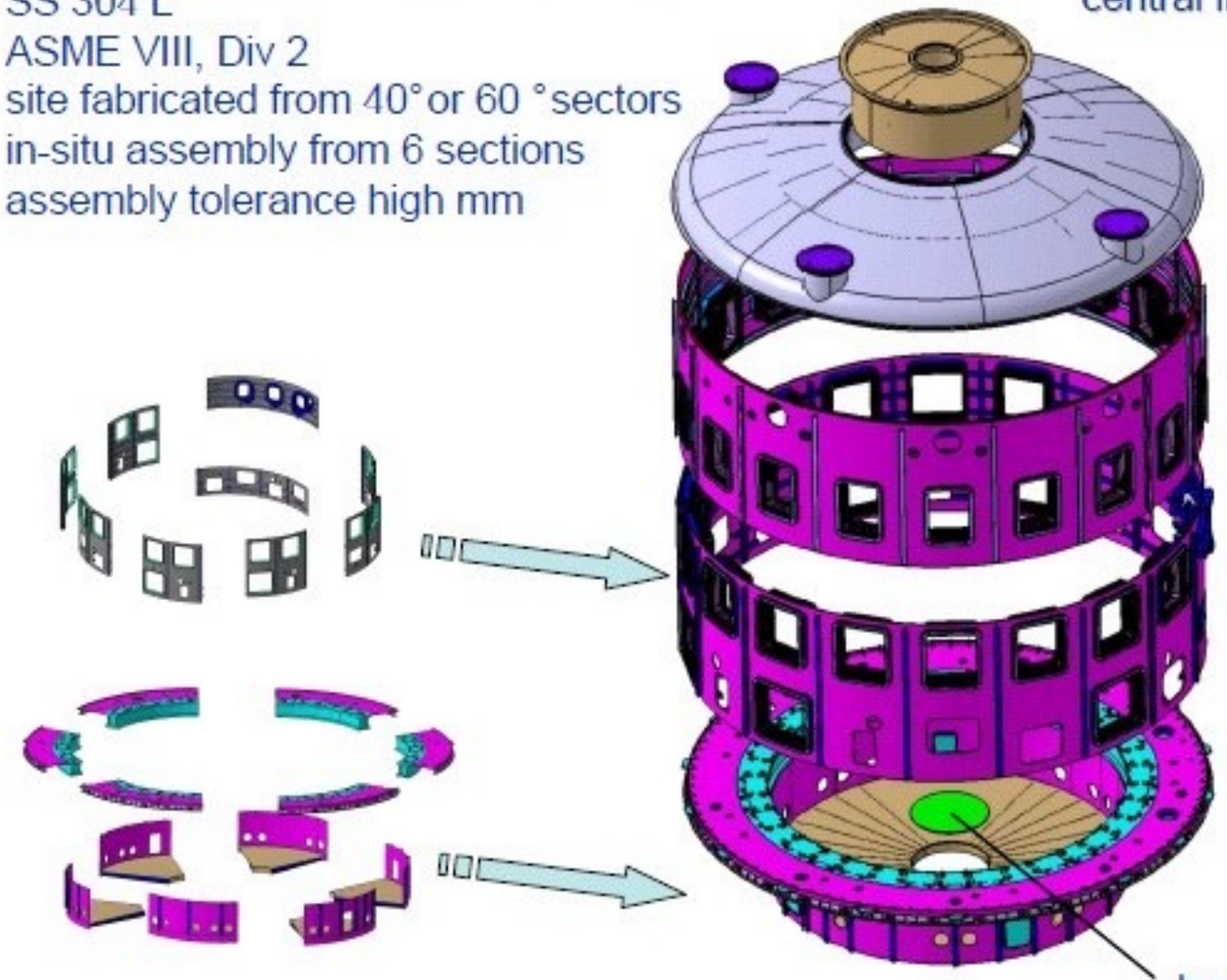
ITER Project is funded by the Department of Atomic Energy (DAE)

Implemented by the Institute for Plasma Research (an autonomous aided institute of (DAE), Gandhinagar

Executed by a special project within IPR, called ITER-India (also called the Domestic Agency) for delivering India’s in-kind commitments

ITER Cryostat

- **Single walled, all-welded structure**
- SS 304 L
- ASME VIII, Div 2
- site fabricated from 40° or 60 °sectors
- in-situ assembly from 6 sections
- assembly tolerance high mm



central lid, Dia 10.7 x 3.7 (110 t)

main lid, Dia 29.0 x 4.1, 558 t
(6 or 9 sectors for transport)

upper cyl, Dia 28.6 x 9.1, 583 t
(6 or 9 sectors for transport)

lower cyl, Dia 28.6 x 9.9, 523 t
(6 or 9 sectors for transport)

base, Dia 29.0 x 6.0, 1105 t

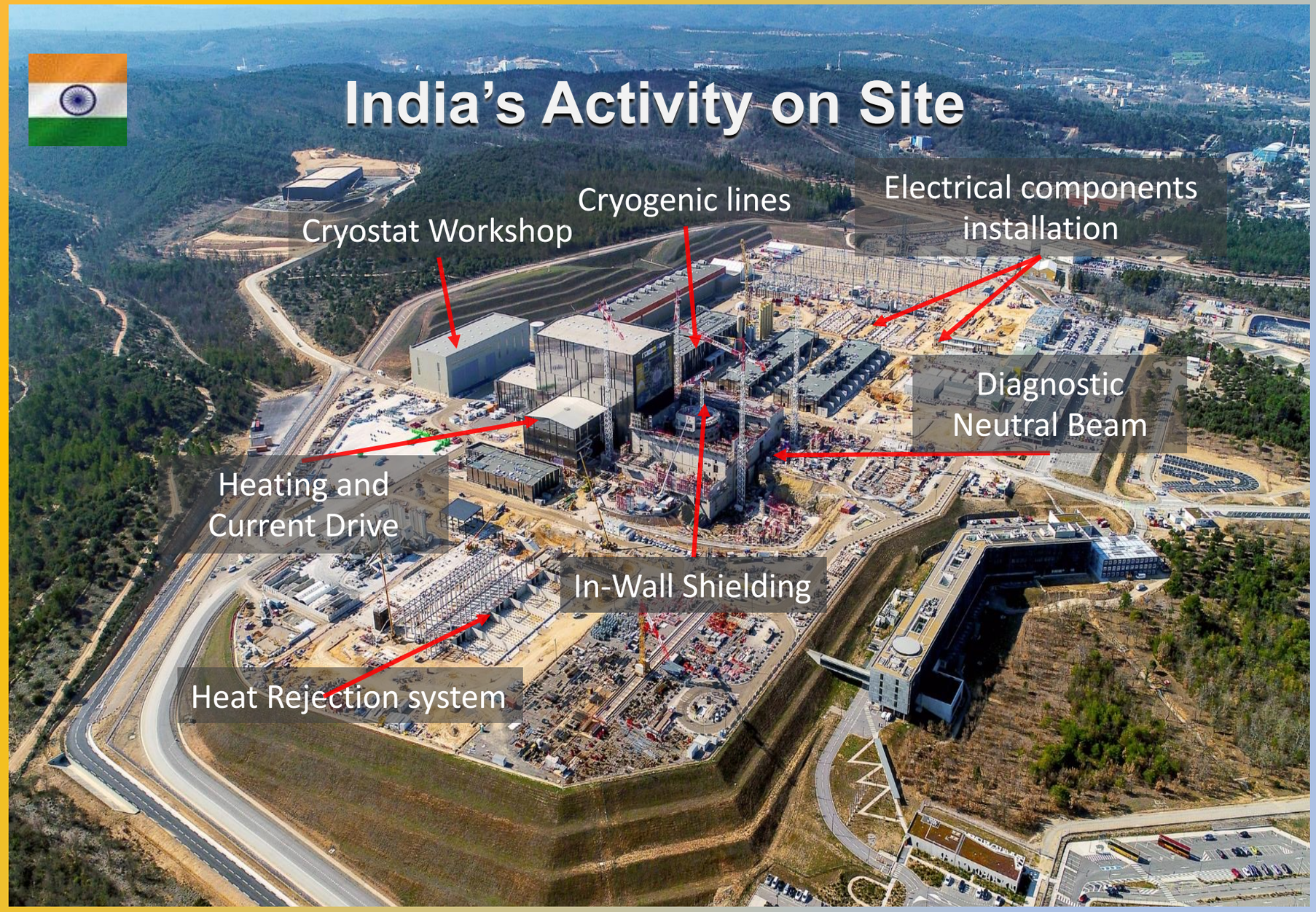
base plug, Dia 4.3 x .06 (6.8 t)

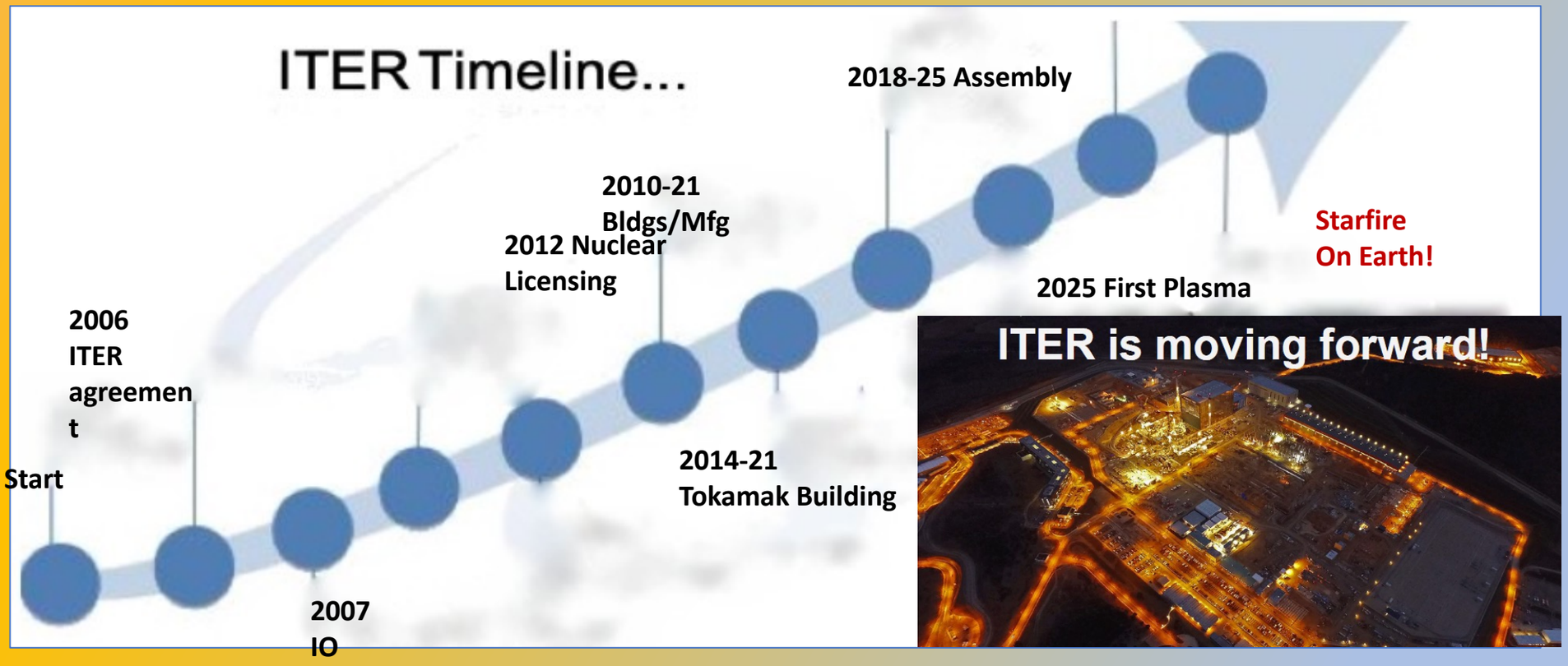
Power Supplies: for RF & DNB systems

Multi-MW power supplies developed to drive the RF based plasma heating systems and the Diagnostic Neutral Beam system

100 kV, 7.2 MW acceleration system power supplies for ion source manufactured in India and working in Padua Italy on ion source dev. Test bed

Pulse Step Modulation based 27-55 kV HVPS for ICRF/EC system


India's Activity on Site
Cryostat Workshop
Cryogenic lines
Electrical components installation
Diagnostic Neutral Beam
Heating and Current Drive
In-Wall Shielding
Heat Rejection system



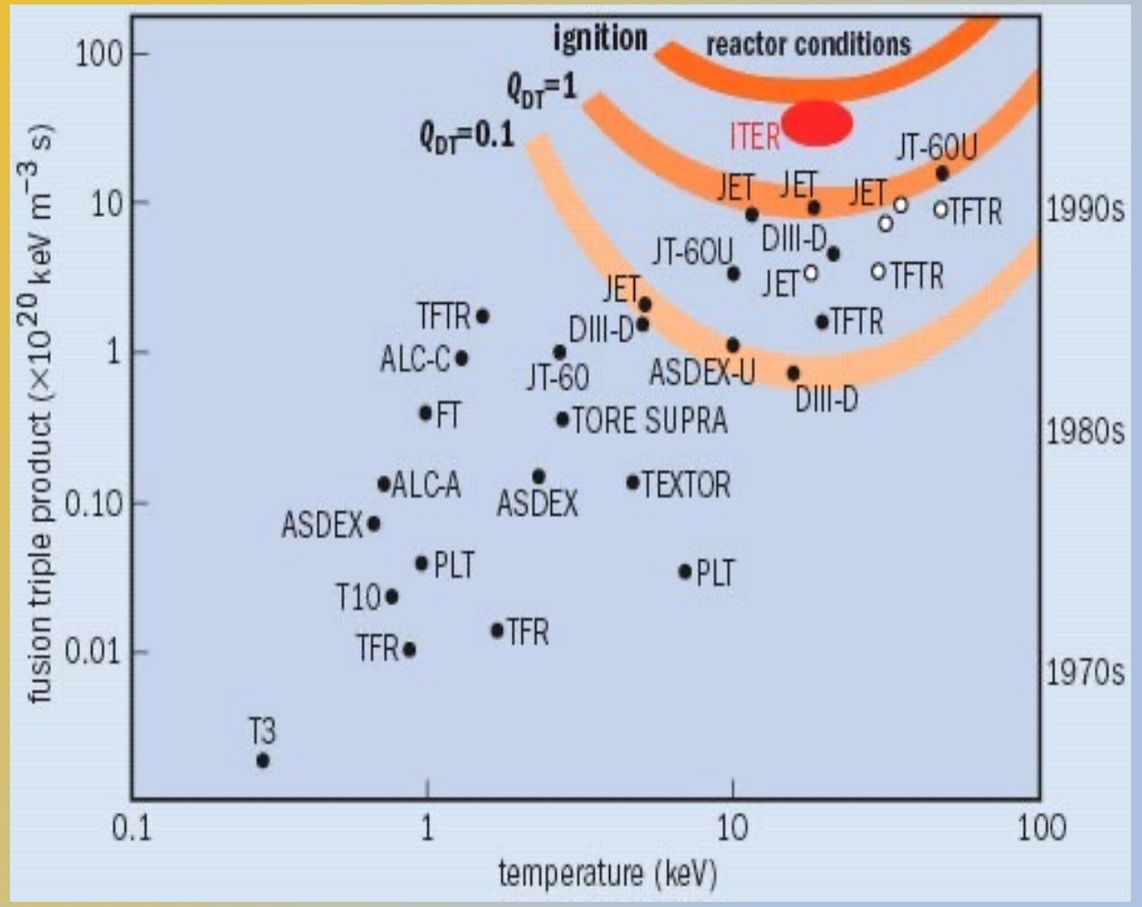
ITER experiments will continue until 2032

Fusion experiments with D and T will start

Full power fusion experiments to continue until 2040.

1950: 72 years of progress

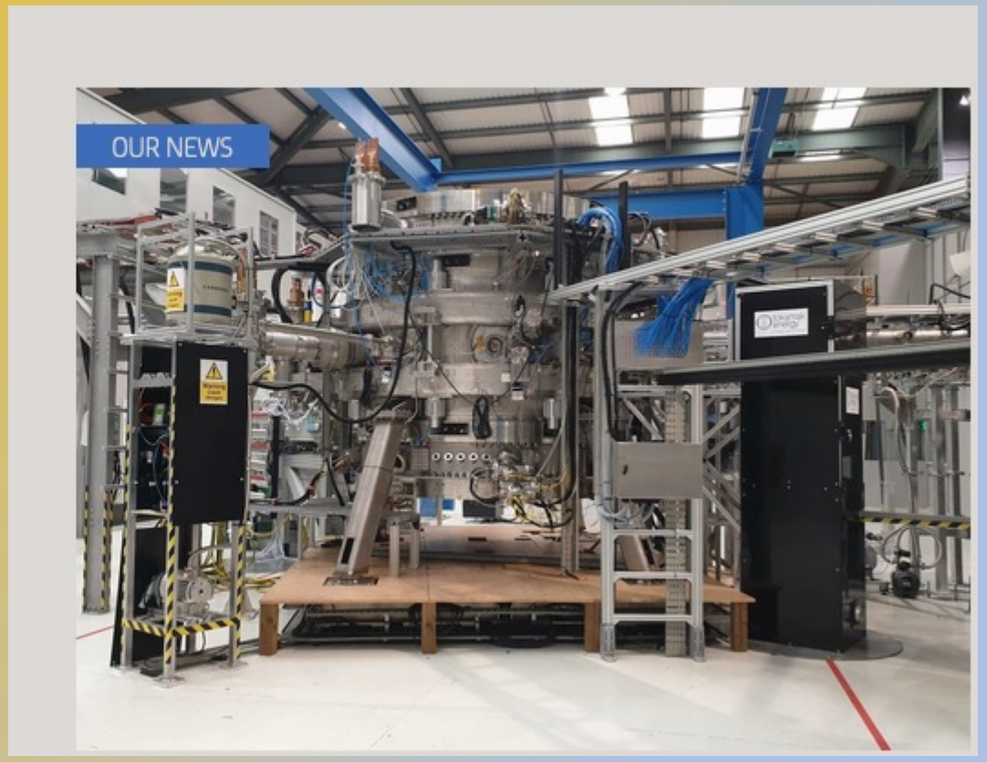
The Fusion Triple Product ($P_i t_E = n_i T_i t_E$) required to reach ignition can be compared with leading edge performance of the devices year-on-year.



Fusion Start Ups

10 March 2022

Tokamak Energy moves closer to commercial fusion: 100M degree plasma...

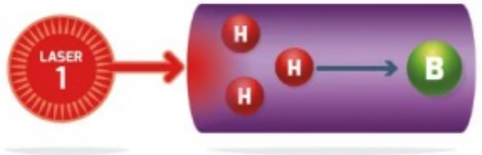


HB11 ENERGY
LASER BORON FUSION

Appl. Sci.
January 2022

Laser ion acceleration

of hydrogen by
picosecond laser pulse
towards B-11 rich fuel



High-power laser pulse

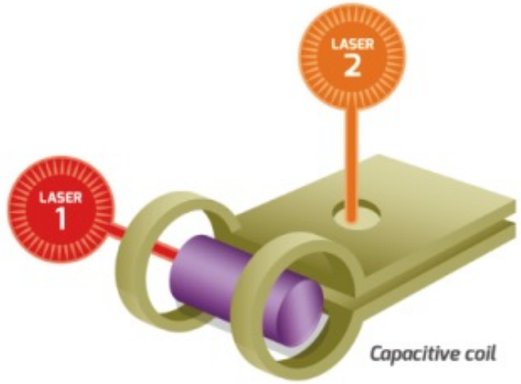
H and B-11 rich fuel pellet

ignites H - B reaction
(non-thermal)

Observed experimentally by:

Magnetic confinement

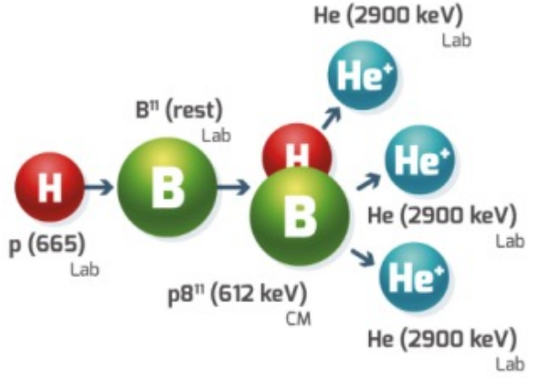
Second laser and capacitive coil



Kilotesla magnetic field
by second laser and capacitive coil
increases reaction yield
in cylindrical shaped fuel

Avalanche reaction

Observed in H B-11 reaction



Further increases reaction yield
by approx. one billion times higher
than previously thought:

1951 -- Sakharov and Tamm Propose Tokamak

1955 -- 1st UN conference -Homi Bhabha : "Fusion in 20 years"

1956 -- Lawson criterion : performance of fusion systems

1958 -- 2nd UN conference : stellarator, pinch, tokamak presented

1961 -- 1st IAEA conference : first plasmas at 1-10 million degrees (ZETA, pinch)

1965 -- Failure of pinches: temperature not as high as expected

1968 -- Novosibirsk IAEA Conference : Success of tokamak

1971 -- Tokamak fever; Conceptual design of reactor

1971 -- First presentation of Inertial fusion systems

1972 -- JET (EU), TFTR(USA), JT60 --proposed; reactor study

1973 – Start of INTOR later ITER

1984 -- JET, TFTR, JT60 start

1985 -- Gorbachev, Reagan : ITER

1991 -- JET first D-T exp

1997 – 16 MW in JET

2005 -- ITER location OK

2007 -- ITER Agreement

2010 -- ITER construction start

2021 – Fusion burn in LLNL

2022 – Fusion burn in JET

2022 – Tokamak Energy attains 100 Million degrees

Conclusions

- Fusion is the answer to the 21st century energy demands
- International efforts have succeeded in its scientific demonstration
- Inertial and Magnetic Confinement approaches have passed critical stages
- India is participating in ITER
- Beyond this, reactor technologies have to be developed
- Private Start ups have joined the effort