FUSION POWER: INEXHAUSTIBLE, CLEAN, BUT?

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WHY FUSION POWER?

- **No carbon emissions** (just Helium, inert gas)
- **Abundant fuel** (extract from seawater; supply for million years)
- **Energy efficiency** (1 kg fuel=10 million kg fossil fuel)
- **No long-lived radioactive waste** (plant components disposable after 100 yrs, not millions)
- **Safety** (fuel consumption size of postage stamp precludes catastrophic accident)

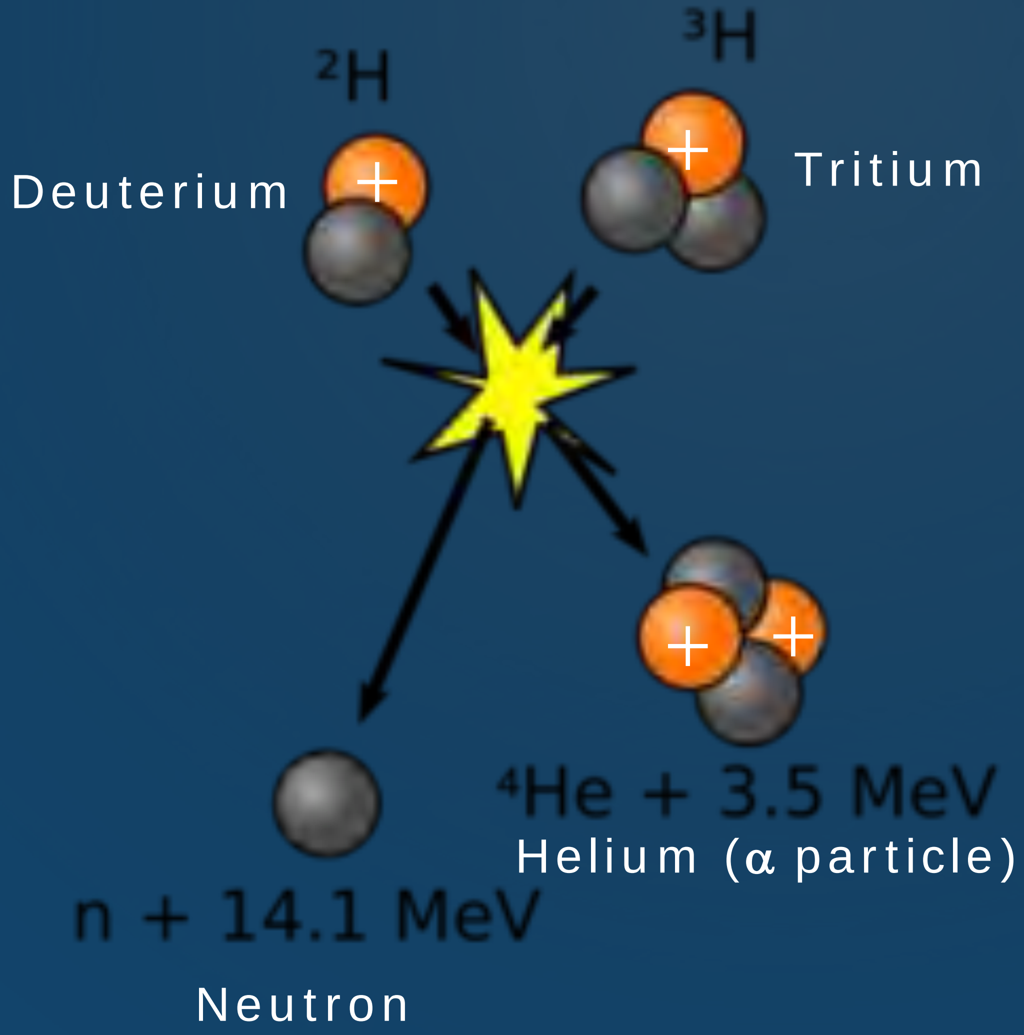
WHAT COULD YOU DO WITH A TERAJOULE? (~3GMS OF DT)

- **You can drive your car for 625,000 miles**
- **You can keep your furnace running for 8 years**
- **You can blow things up! 1TJ = 250 ton of TNT**

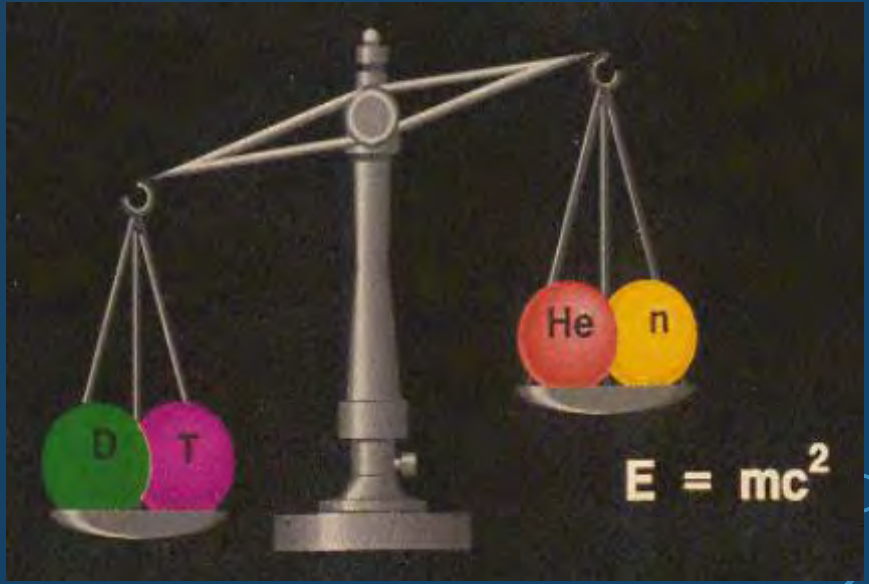
A BIT OF HISTORY OF FUSION POWER

- 1938 Hans Bethe Nobel Prize for explaining solar fusion (Carbon cycle)
- 1942 Enrico Fermi and Edward Teller Study ignition of hydrogen and heavy hydrogen for a Super-bomb
- 1950 Andrei Sakharov proposes magnetic confinement of fusion plasma (Tokamak)
- 1951-1952 First successful large ignition of D+T in weapons
- 1952-Present: Many unsuccessful Magnetic Confinement experiments
- 1967 John Nuckolls proposal for Laser Fusion by Inertial Confinement
- Still in R&D

WHAT IS NUCLEAR FUSION?



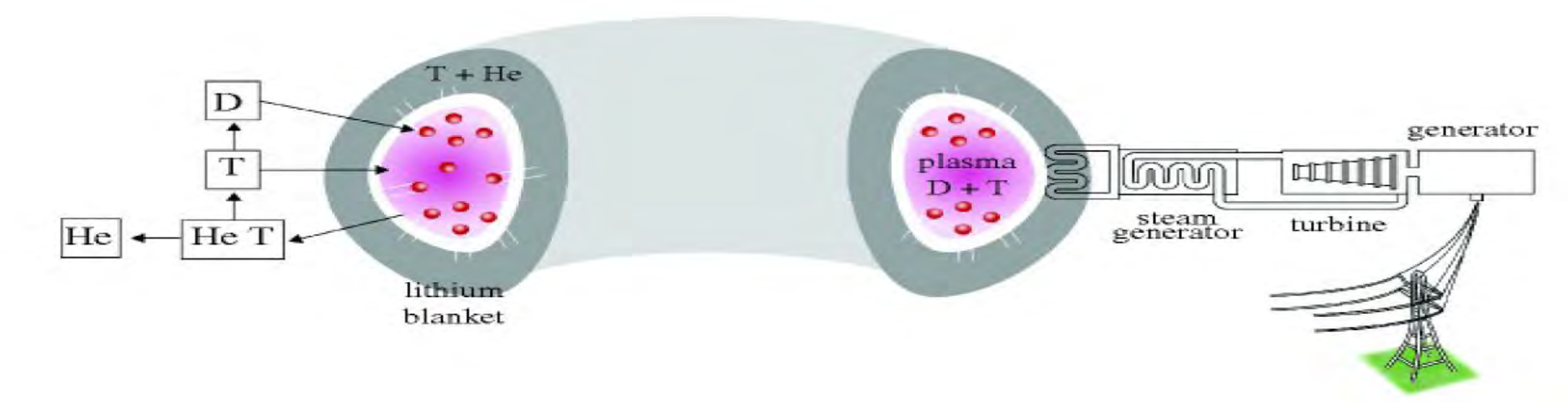
Mass Deffect=E=mc^2=Energy
(Unequal binding energy!)



D + T → α(3.5MeV)+n(14.1MeV)+Radiation

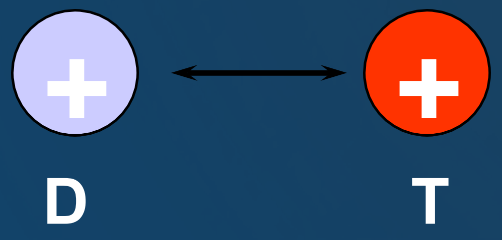
WHO DOES WHAT

- ***Alpha particle*** HEATS the plasma to sustain HIGH TEMPERATURE to continue D+T burning reaction
- ***Radiation*** (in the form of X-rays) escapes
- ***Neutron*** is CAPTURED in a MODERATOR, its energy converted to heat, which is captured in a heat exchanger to produce steam, drive a turbine, etc.

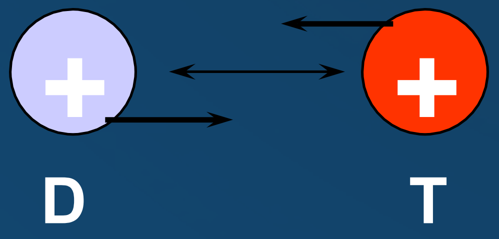


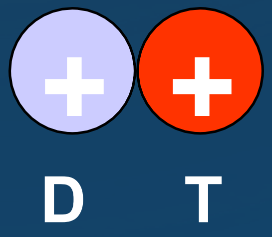
HOW DO WE “FUSE” DIFFERENT NUCLEII?

- **Probability for fusion reactions to occur is low at low temperatures because of Coulomb repulsion force.**



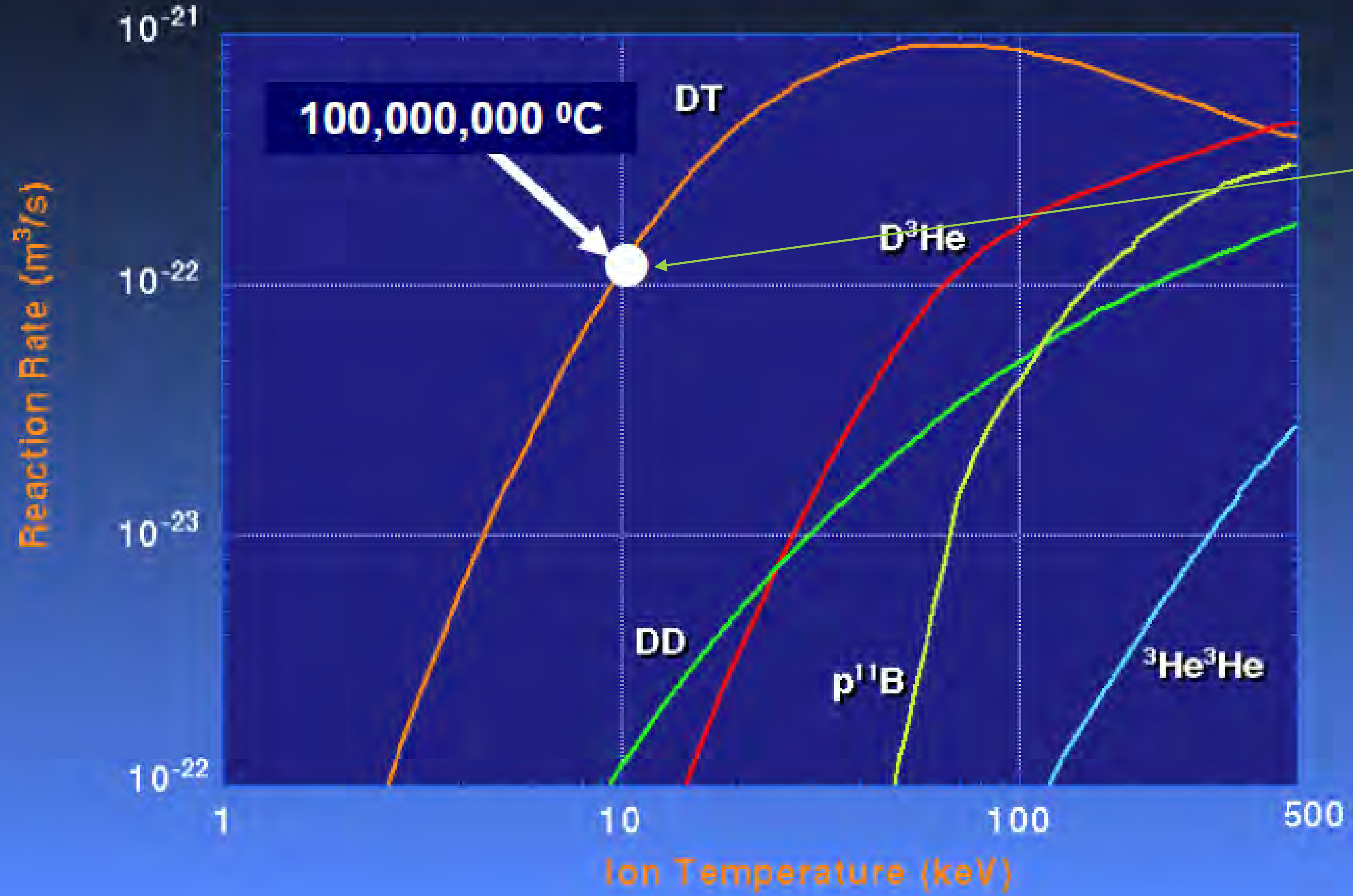
- **If the ions are sufficiently hot (i.e. large random velocity) then they can collide by overcoming Coulomb repulsion**





Need heating to 100 Million Degrees

Fusion doesn't come easy



Plasma Heating Done by Alpha Particles 4.5 MeV Energy

(neutrons and radiation escape!)

WHAT SUBSTANCES FUSE (REALATIVELY) EASILY?

Fusion Reaction		Temperature Needed (in Million Degrees)	Reaction Energy (in keV)
D + T	^4He + n	100-200	17,600
D + ^3He	^4He + p	~700	18,300
D + D	^3He + n	~400	~4,000
	T + p	~400	~4,000

Fusion Cross-Sections and Reactivities

Reaction	σ (10 keV) (barn)	σ (100 keV) (barn)	σ_{max} (barn)	ϵ_{max} (keV)
$D + T \rightarrow \alpha + n$	2.72×10^{-2}	3.43	5.0	64
$D + D \rightarrow T + p$	2.81×10^{-4}	3.3×10^{-2}	0.096	1250
$D + D \rightarrow {}^{3}He + n$	2.78×10^{-4}	3.7×10^{-2}	0.11	1750
$T + T \rightarrow \alpha + 2n$	7.90×10^{-4}	3.4×10^{-2}	0.16	1000
$D + {}^{3}He \rightarrow \alpha + p$	2.2×10^{-7}	0.1	0.9	250
$p + {}^{6}Li \rightarrow \alpha + {}^{3}He$	6×10^{-10}	7×10^{-3}	0.22	1500
$p + {}^{11}B \rightarrow 3\alpha$	(4.6×10^{-17})	3×10^{-4}	1.2	550
$p + p \rightarrow D + e^{+} + \nu$	(3.6×10^{-26})	(4.4×10^{-25})		
$p + {}^{12}C \rightarrow {}^{13}N + \gamma$	(1.9×10^{-26})	2.0×10^{-10}	1.0×10^{-4}	400
${}^{12}C + {}^{12}C$ (all branches)		(5.0×10^{-103})		

FUSION ENERGY PRODUCTION NECESSARY CONDITIONS

- ***High Temperatures** to OVERCOME Coulomb barrier*
- ***Confine Hot Plasma** for a minimum amount of time to get useful energy out of it*
- ***Isolate Hot Plasma** to Prevent Energy Lossess (e.g. from touching the walls)*
- ***Prevent Plasma Instabilities** (turbulence drains energy fast and cools/extinguishes plasma burning)*

FUSION NECESSARY CONDITIONS: LAWSON'S CRITERIA

Net power = Efficiency × (Fusion − Radiation loss − Conduction loss)

- **Net power** is the excess power beyond that needed internally for the process to proceed in any fusion power plant.
- **Efficiency** is how much energy is needed to drive the device and how well it collects energy from the reactions.
- **Fusion** is rate of energy generated by the fusion reactions.
- **Radiation loss** is the energy lost as light (including X-rays) leaving the plasma.
- **Conduction loss** is the energy lost as particles leave the plasma, carrying away energy.

LAWSON'S CRITERIA OF MINIMUM CONDITIONS

For the deuterium–tritium reaction, the physical value is at least

$$n\tau_E \geq 1.5 \cdot 10^{20} \, \frac{\mathrm{s}}{\mathrm{m}^3}$$

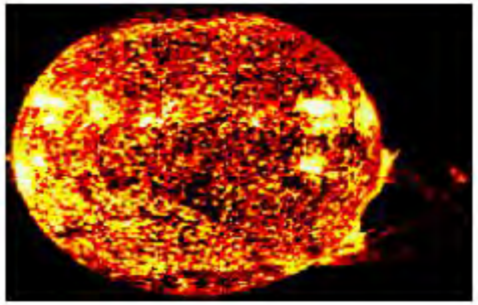
The minimum of the product occurs near $T = 26\,\mathrm{keV}$.

$$\begin{aligned} nT\tau_E &\propto nT\left(n^{1/3}/P^{2/3}\right) \\ &\propto nT\left(n^{1/3}/\left(n^2T^2\right)^{2/3}\right) \\ &\propto T^{-1/3} \end{aligned}$$

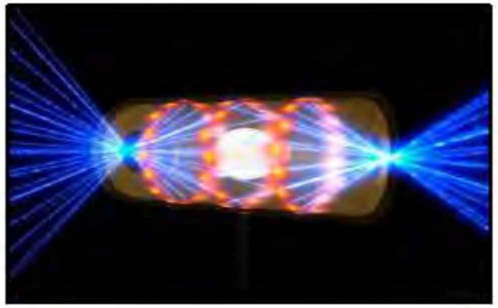
The triple product is only weakly dependent on temperature as $T^{-1/3}$

PLASMA CONFINEMENT METHODS

- **Gravitational Confinement** (300 W/m^3)
  - In a deep gravitational well, even fast particles are trapped.
  - Very slow: $\tau_E \sim 10^6$ years, burn-up time = 10^{10} years



- **Inertial Confinement** (10^{28} W/m^3)
  - Heat and compress plasma to ignite plasma before constituents fly apart.
  - Like a little H-bomb
  - Capsules would need to be burned with high gain, high rep rate for reactor practicality

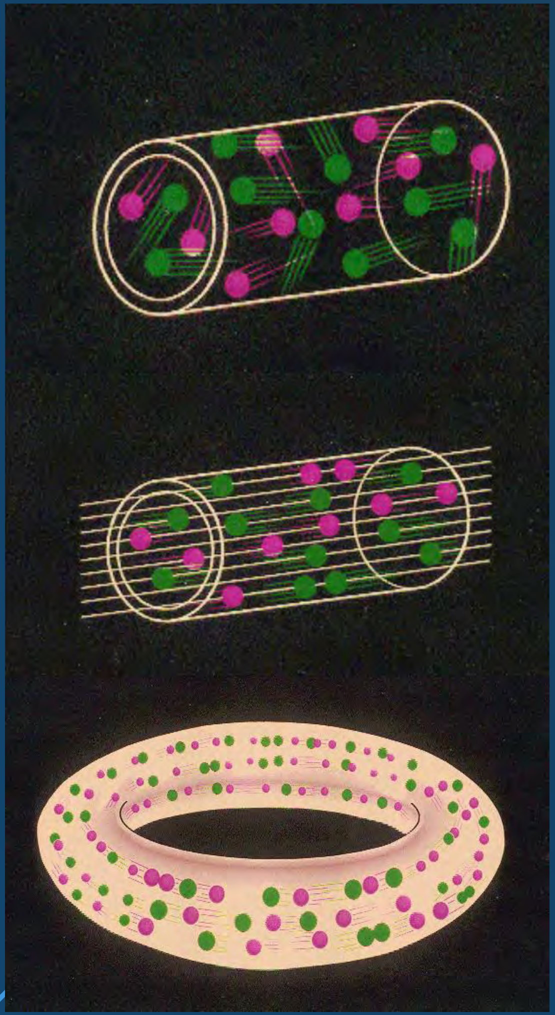


- **Magnetic Confinement** (10^7 W/m^3)
  - Uses the unique properties of ionized particles in a magnetic field

PRINCIPLE OF MAGNETIC CONFINEMENT

- **Fusion fuel is heated by pasing an electric current through the D+T gas filling in a vacuum tube, creating hot "ionized plasma."**
  - Like a fluorescent light bulb filled with D+T Gas
- **D+T Plasma must then be confined long enough to release net energy (many seconds)**
  - **We use magnetic fields to form a "magnetic bottle"**
  - **The "magnetic bottle" must prevent loss of energy (escaping heat, radiation)**
- **The D+T Plasma has to be "stable"**
  - **no kinks or other plasma instabilities that drain energy and quench the fusion fire…**

PRINCIPLE OF MAGNETIC CONFINEMENT

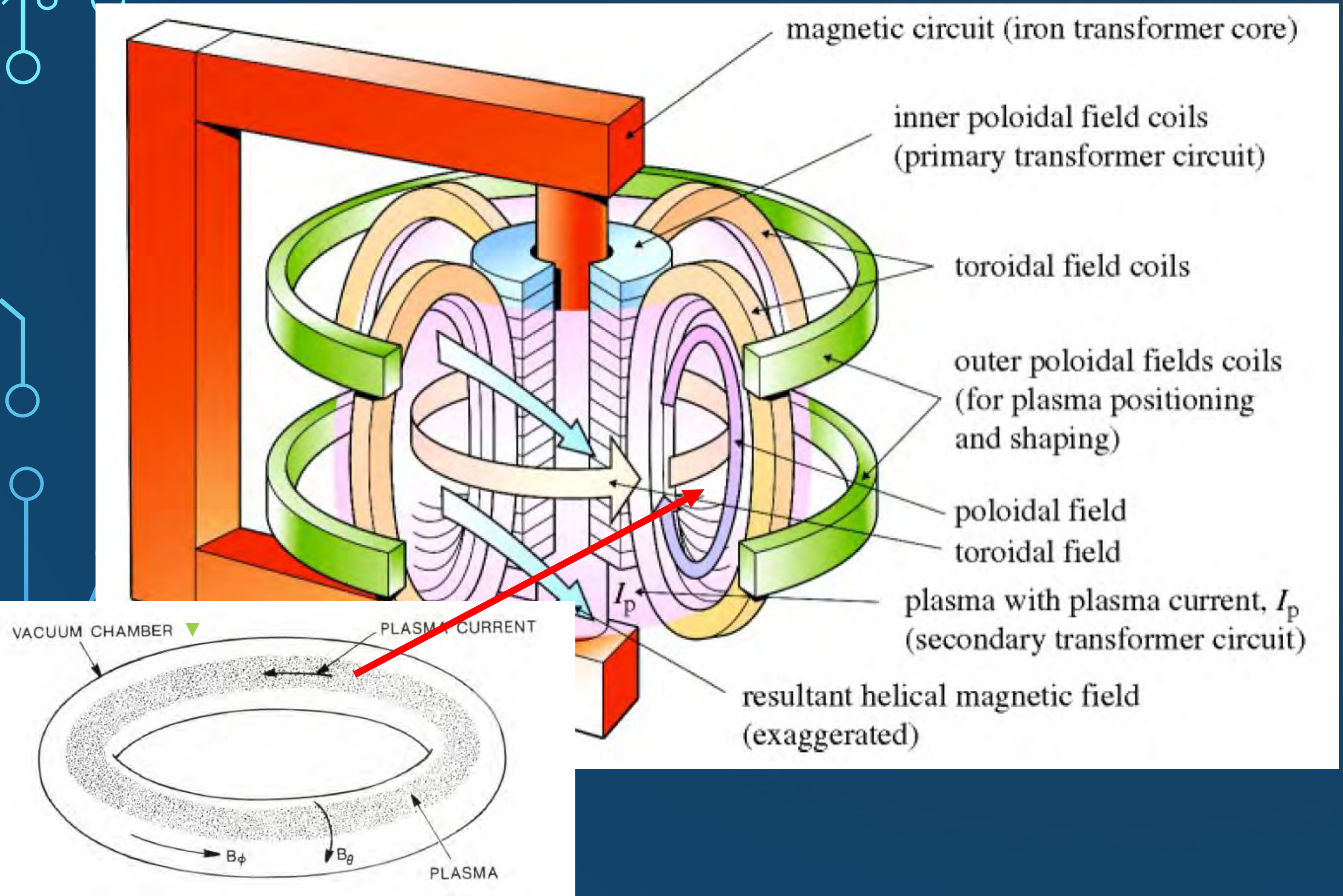


Fast-moving particles in a simple container would quickly strike the walls, giving up their energy before fusing

Magnetic fields exert forces charged particles that inhibit and direct the motion of the particles

Magnetic fields can be fashioned into complex configurations sometimes called magnetic bottles

TOKAMAK EXAMPLE OF MAGNETIC CONFINEMENT



BIG TRANSFORMER

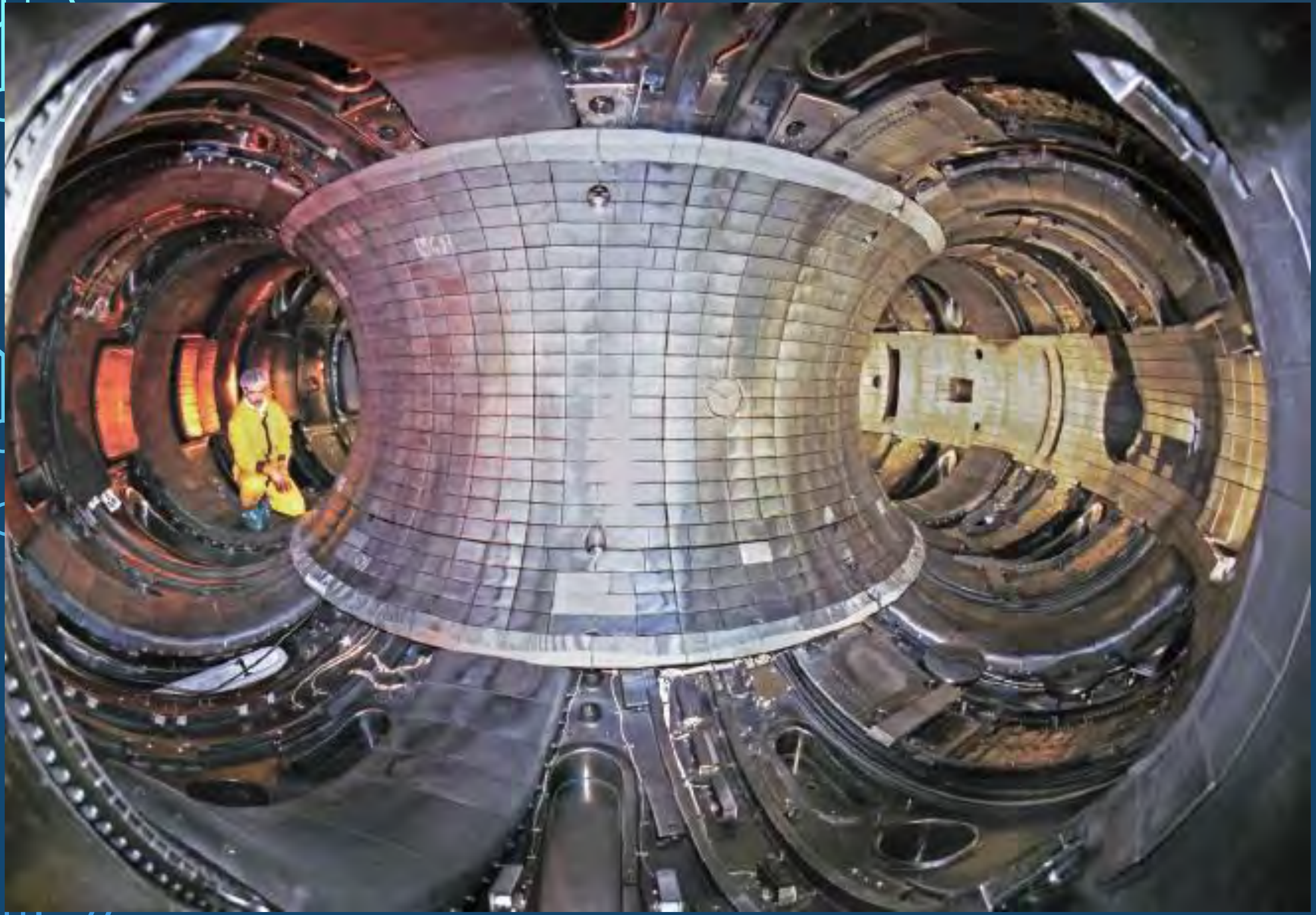
"Donut" vacuum tube is the secondary of the transformer

The induced current in the secondary heats the plasma

Additional coils supply a "shaped" (poloidal) magnetic field to insulate the plasma from the torus walls

Invented by Nobel laureate A. Sakharov

THE "INSIDES" OF A TOKAMAK



Latest TOKAMAK version is "ITER"

International Thermonuclear Experimental Reactor

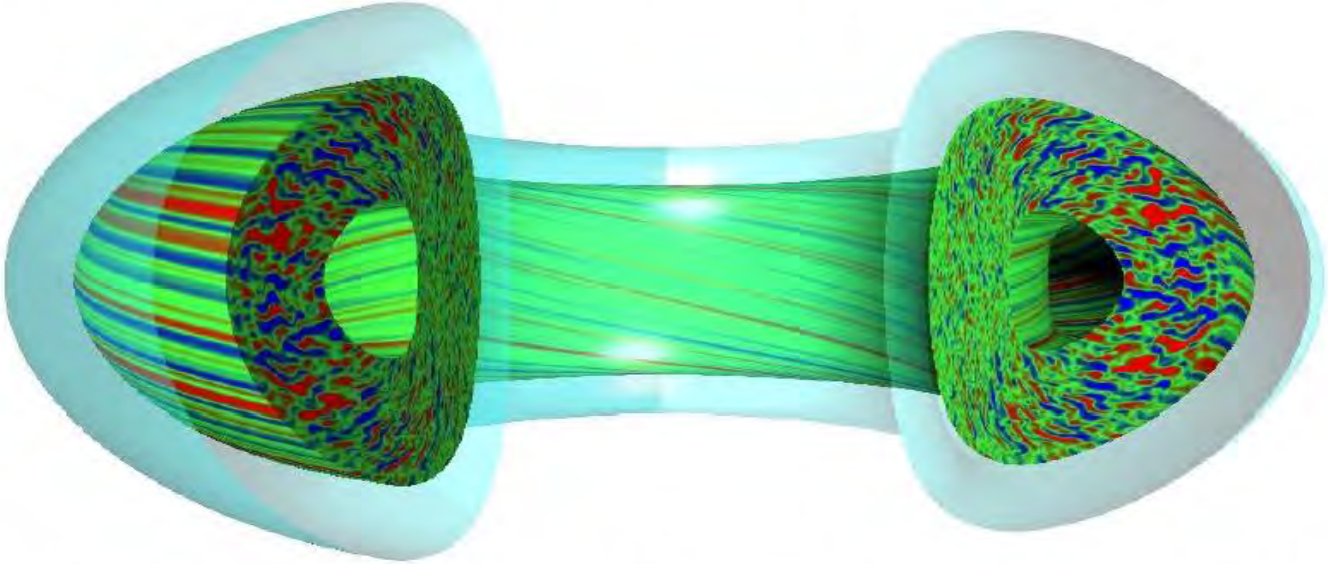
Fusion power:500-700 MW
Pulsed Burn time: ~300 sec
Low energy density: 10^7w/m3

Slated for completion 2025
Many delays and over budget
Will be fueled with D+T in …2032!

BIGGEST TOKAMAK PROBLEM: TURBULENCE

Turbulence is rampant in high energy plasmas, degrading confinement

- Early calculations made overoptimistic predictions of tokamak confinement
- *Turbulence* was not taken into account!



One frame of a simulation of turbulence in the DIII-D using GYRO (J. Candy, General Atomics)

- Turbulent eddies carry heat and particles out of the plasma **hundreds of times faster** than random collisions alone would

PRINCIPLE OF INERTIAL CONFINEMENT FUSION (ICF)

Relies on the INERTIA of the fuel mass to provide confinement of the burning fusion fuel

Principle demonstrated in H-bombs and OUR SUN!!!

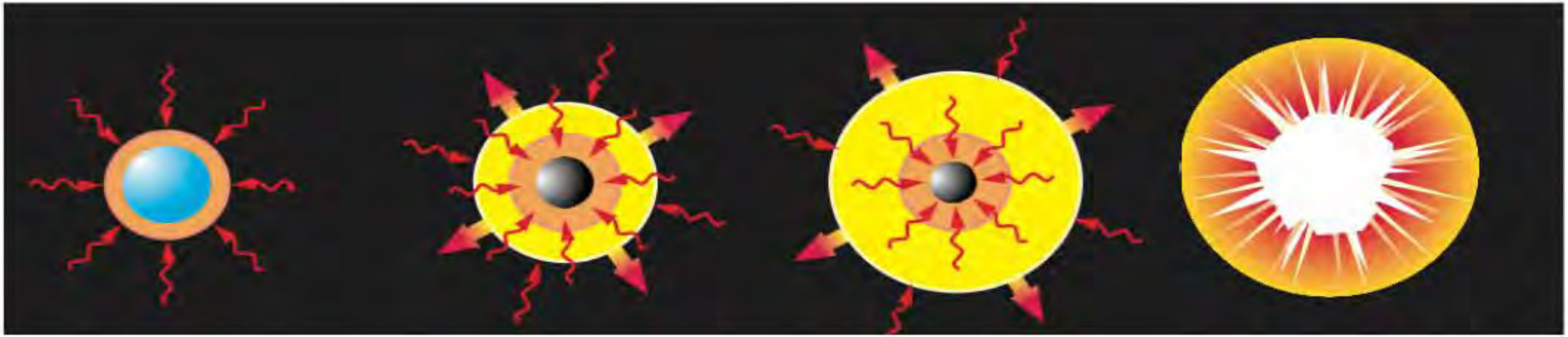
4 steps involved, using lasers or ion beams to:

1. Ablate surface (rocket effect)
2. Compression by ablated matter blowoff (Newton's 3rd law)
3. Ignition of focus point by shock waves
4. Fusion flame spreads through the compressed D+T fuel mass

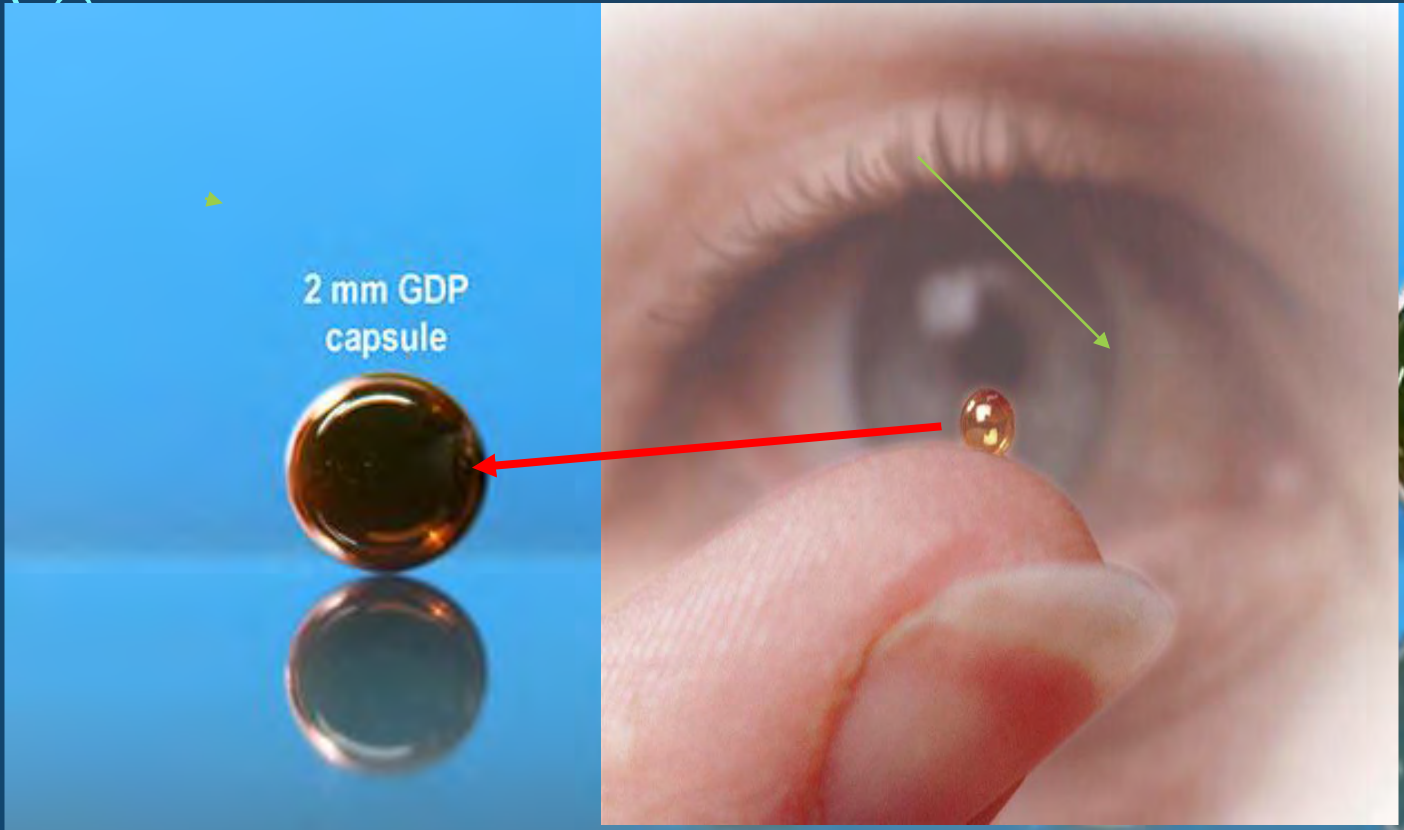
KEY IS VERY HIGH COMPRESSION for HIGH DENSITY (X1000 or more normal density)

BASICS OF INERTIAL FUSION

Using powerful laser or particle beams to compress a tiny pellet



ICF FUSION PELLETS VS. MINI-H BOMB



Yield: ICF Capsules=~1/7 ton TNT

W80=150 kTons

PRINCIPLE OF INERTIAL CONFINEMENT

The number of thermonuclear reactions n per second is

$$dn/dt=NdNt\{\sigma\ v\}$$

where Nd, NT is number of D or T particles, and {σ v} is the fusion reaction average cross section

And for an equimolar DT mixture,

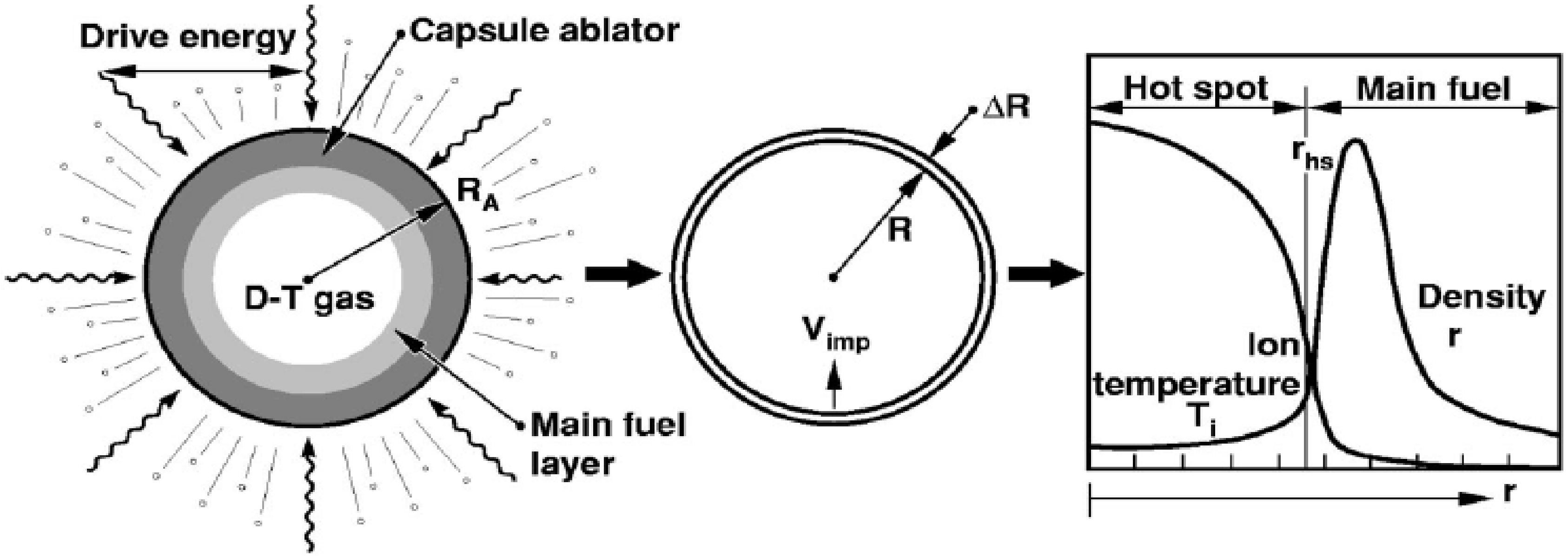
$Nd=NT=(1/2\ N_0-n)$ where N_0 is the initial total number density

If we define the burn fraction by ϕ=2n /N0, and assume Maxwell averaged cross section is nearly constant over burn duration, then

the burn efficiency is: $\phi/(1-\phi)=[(N_0T)/2]\ \{\sigma\ v\}$

where T is confinement time and N_0 is the initial total number density

ICF CAPSULE SPECS



Driver—target coupling
⇒ $I_r \lesssim 10^{15}$ W/cm^2 or $\lesssim$300 eV

To control:
¥ Absorption/preheat
¥ X-ray conversion
¥ Transport/drive

Symmetry:	$\frac{R_A}{r_{hs}}$ =	Convergence ratio	≈ 25—45 ⇒	Coupling $\eta \approx$ 10—15%
Stability:	$\frac{R}{\Delta R}$ =	In-flight aspect ratio	≈ 30—40 ⇒	$I_R \gtrsim 4 \times 10^{14}$ W/cm^2 or 250 eV Surface <1000
Ignition:	¥ $T_{i,\,hs}$ = 10 keV ¥ ρr_{hs} ≈ 0.3 g/cm^2		⇒	V_{imp} 3—4 × 10^7 cm/s for E_{driver} = 1—2 MJ

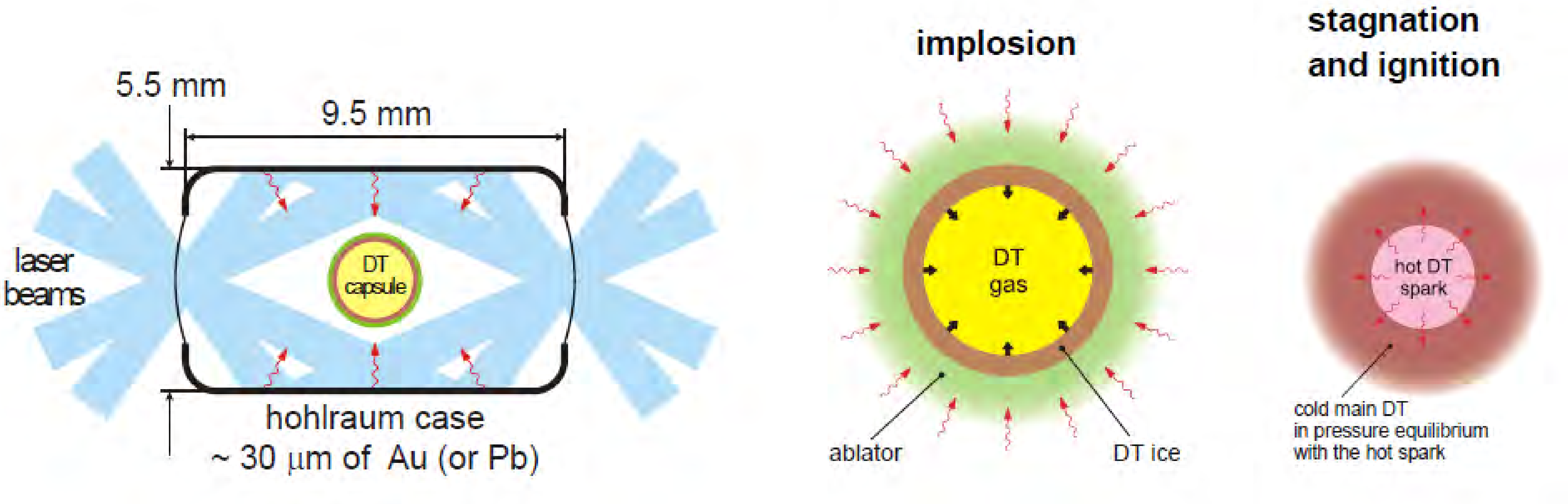
Compress by factor ~1000

Timing=~ 1-2 nanoseconds

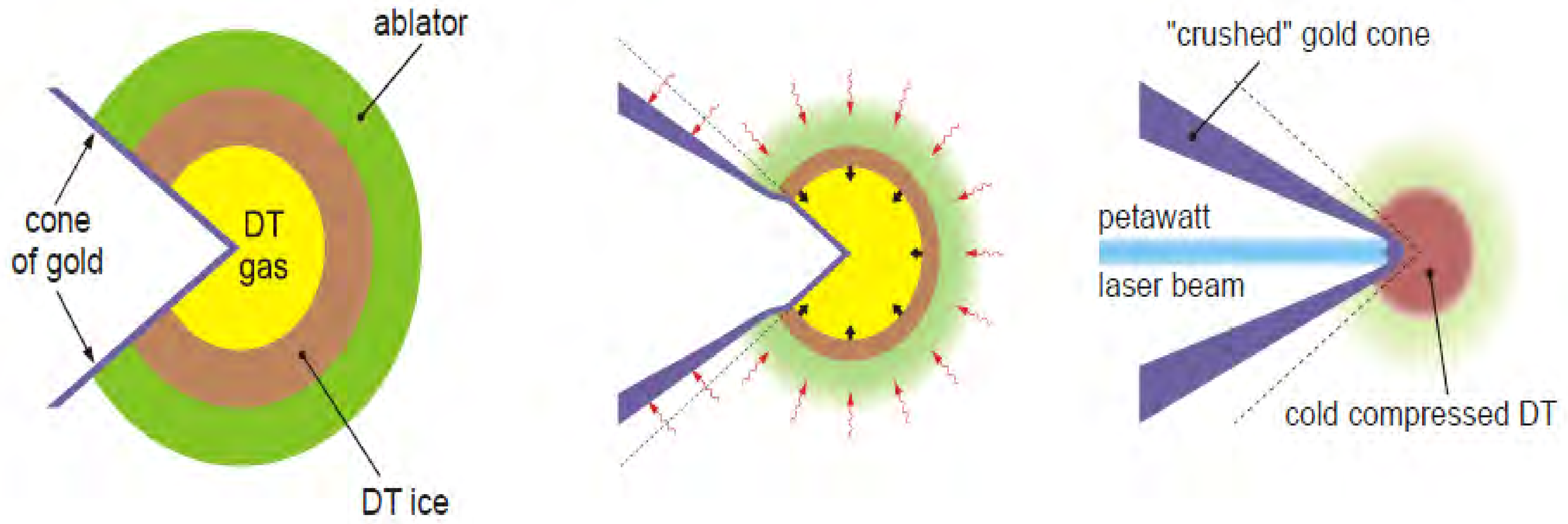
Heating "Hot Spot" to 10^8 deg

Symmetry kept to <1%

Traditional Ignition



Fast Ignition



Design of ICF experiments and interpretation of results requires codes which treat a full spectrum of processes

HYDRA code

Equation-of-State
Inline, tables
LTE & NLTE

Magnetic fields
3D resistive MHD

Laser raytrace and deposition

ALE hydrodynamics
Block structured mesh

Interface reconstruction

Electron, ion transport
– Flux limited diffusion
– Non-local transport

Heavy ion deposition
choice of stopping power models

Neutron transport
Treated in free streaming limit

Radiation transport
– Multigroup diffusion
– Implicit Monte Carlo
– Radiation characteristics
– 1D S_N

Charged particle transport
Extension of diffusion

Opacity models
– Inline or tables
– Online client server
– LTE, NLTE

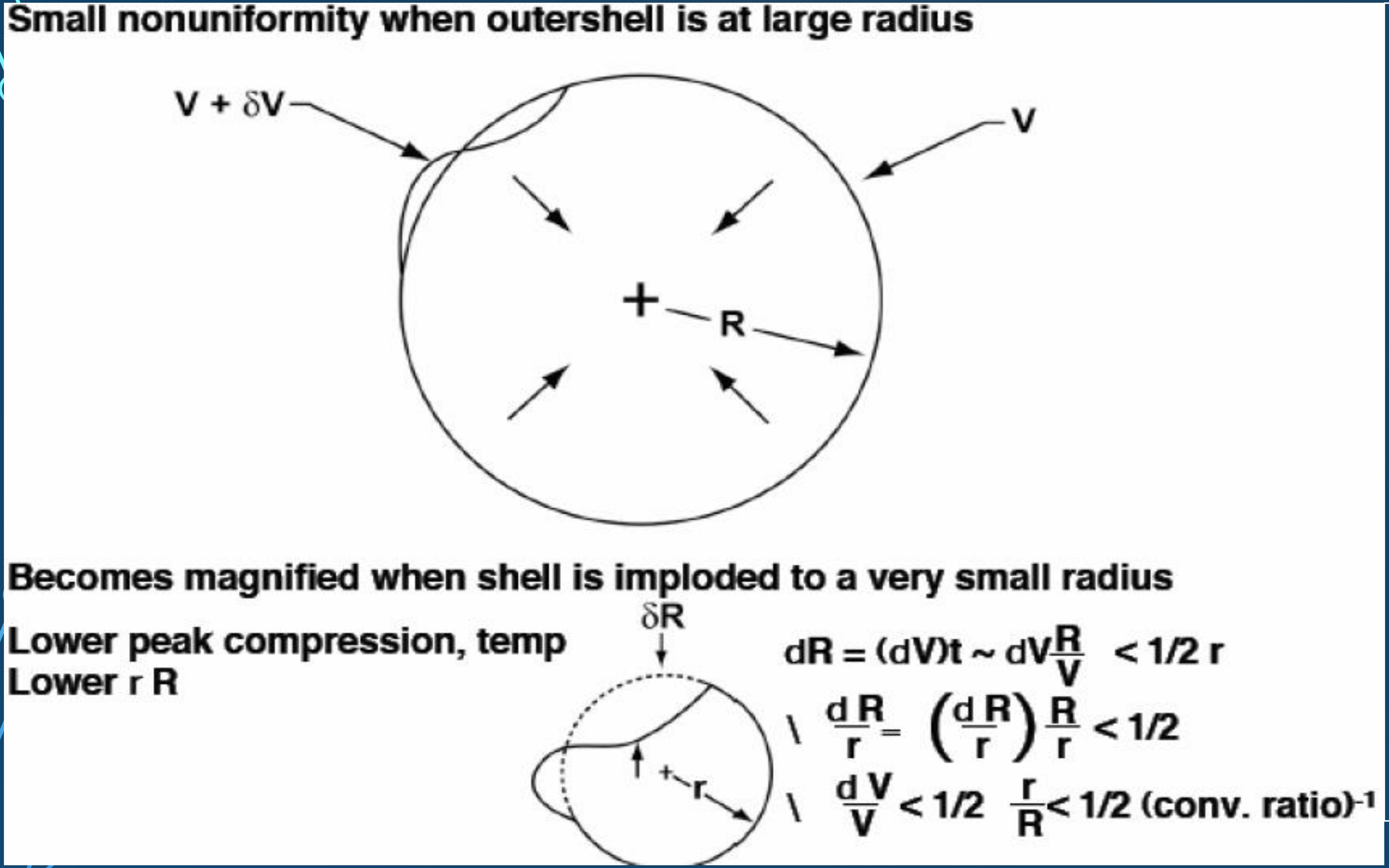
Thermonuclear burn

HYDRA runs on workstations, SMP and massively parallel platforms - on up to 8192 processors to date

HYDRA is an export restricted code

M.M.Marinak, et al., Phys. Plasmas, **8**, 2275 (2001)

BIGGEST PROBLEMS WITH INERTIAL CONFINEMENT



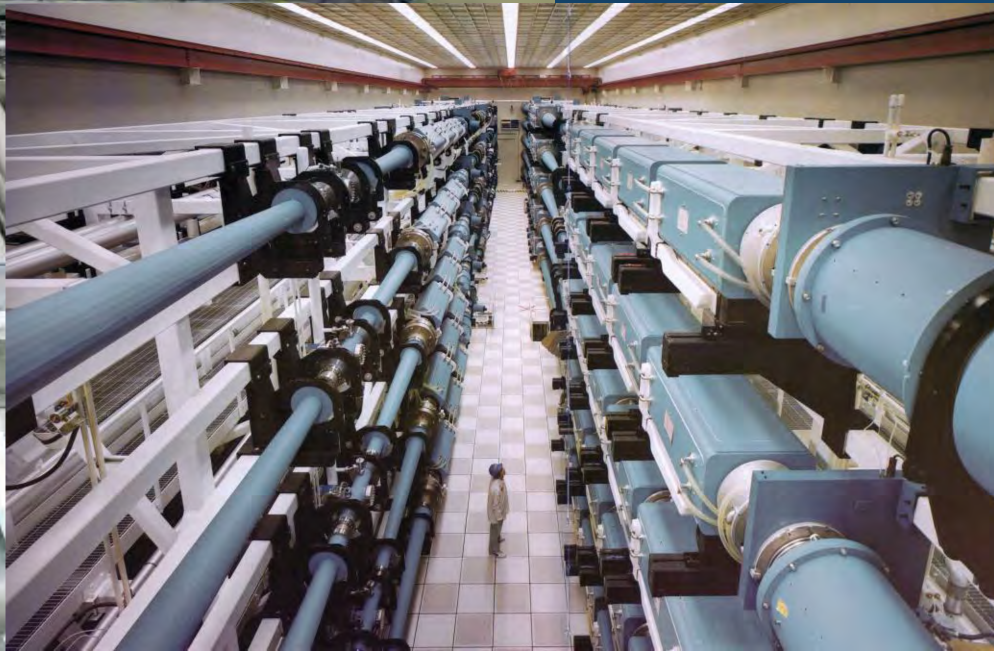
R-T Instability

Plasma Instability

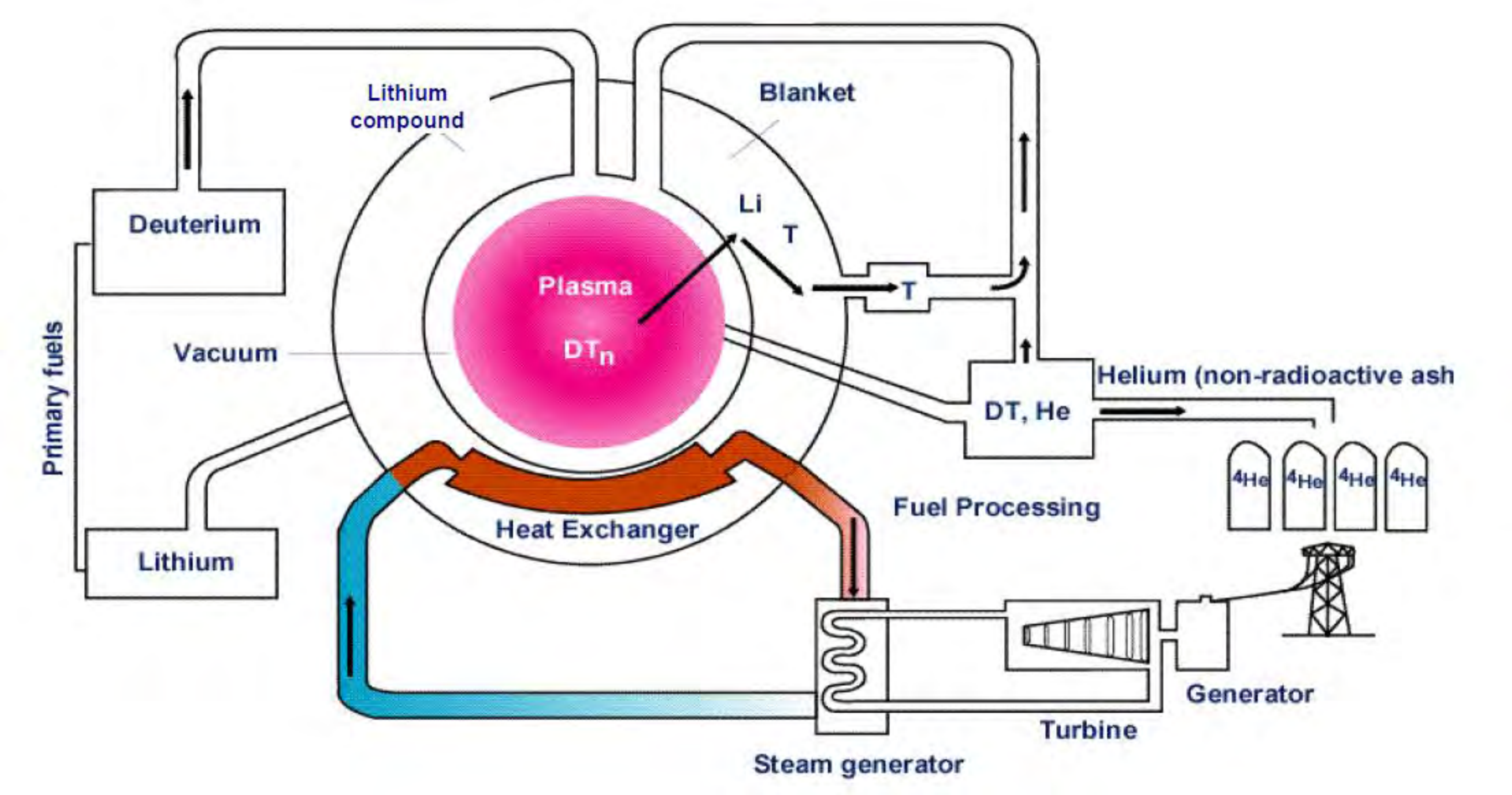
Pre-heat (enemy of compression)

Proliferation (is a micro H-Bomb)

LASERS FOR INERTIAL CONFINEMENT (LLNL NIF)



TYPICAL FUSION PLANT



ISSUES

For Magnetic Fusion, the primary issues are optimizing the configuration for effective confinement of the fuel, managing turbulence, and extending from pulsed to steady-state operation.

For Inertial Fusion, the primary issues are optimizing the techniques for compressing the fuel in a stable manner, managing preheat (enemy of compression) and turbulence (reducing energy loss)

For both,

- identifying materials that provide long life and low induced radioactivity in a harsh, neutron-rich environment.
- Manage proliferation aspects (copious producers of Plutonium)

For both, optimizing the total system to reduce projected development and capital cost and demonstrating methods for ensuring reliability and cost-effective maintenance.

THE FUTURE?????

- Solving PLASMA INSTABILITY requires clever solutions (manpower and money)
  - Training people in plasma physics
  - Providing super-computers to simulate plasma behavior
  - Experimental facilities to run tests
- Money: Each experimental facility costs close to 3 to 10 Billions dollars
- Currently, for USA, UK, France, Russia and China, the funding comes from the military Nuclear Weapons programs
- Project Management: all fusion facilities ran over schedules and budgets by factors of 3 to 5; e.g. NIF (US) went from $1B to $10B, and 6 yrs late

ACKNOWLEDGMENT AND BIBLIOGRAPHY

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