Fusion Energy: The Prize, The Pathways, The Prospects

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The Prize: Realizing Fusion Energy

- Positive for energy demand, environment, economy, sustainability
- Fusion can provide:
    1) Clean energy source for heat, electricity, hydrogen
    2) Virtually inexhaustible fuel supply
    3) No GHG or air pollution (He is the “ash”)
    4) No risk of nuclear accident (no public evacuation)
    5) Highest energy density & …minimal land impact
    6) Best energy payback ratio (EPR) & life cycle assessment (LCA - tonnes CO_2/GWHe) of all sources (solar, wind, fission)
- Fusion will become an overarching catalyst for wealth & job creation
- Fusion R&D is proceeding inexorably worldwide

Fusion – Energy Applications

- Base-load electric power generation (on-demand – 24/7)
- Production of hydrogen for fuel cells/synthetic fuels
- Heat for chemical processing, etc.
- Desalination of sea-water
- Clean up fission waste
- Production of fissile fuel for fission reactors
- Hazardous nuclear waste processing

- Create new industries

- Fusion-fission hybrids (fission fuel extended, waste burned)
  - could be an interim step enroute to pure fusion systems

Key Enabling (& Spinoff) Technologies

- **Heating** (particle beams, electromagnetic waves – incl lasers)
- **High field magnets** (diverse applications)
- **High power lasers** (diverse applications)
- **Precision optics** and opto-electronics
- **Photonics** (superseding electronics)
- **Diagnostics** (sensors, instrumentation)
- **Additive manufacturing**
- **Robotics** (remote handling, line replacement modules)
- **Materials & nanotech** (lasers, optics, targets, chamber materials)
- **Plasma** control, data, analysis, etc (AI & computer modeling)
- **Fueling, tritium breeding & processing**
- **Cryogenics**
- **Systems engineering** (design, construction, IP)

- **Will have large economic impact**

Fusion Reactions & Power Generation
- requirements for fusion

Fusion reactions require high particle energy (= temperature)

- to overcome Coulomb repulsion of (+ve) nuclei
- temperature for ignition: **$T_{ign} \geq$ 100 million deg C**
- all matter is ionized at high T – "plasma" (4th state)

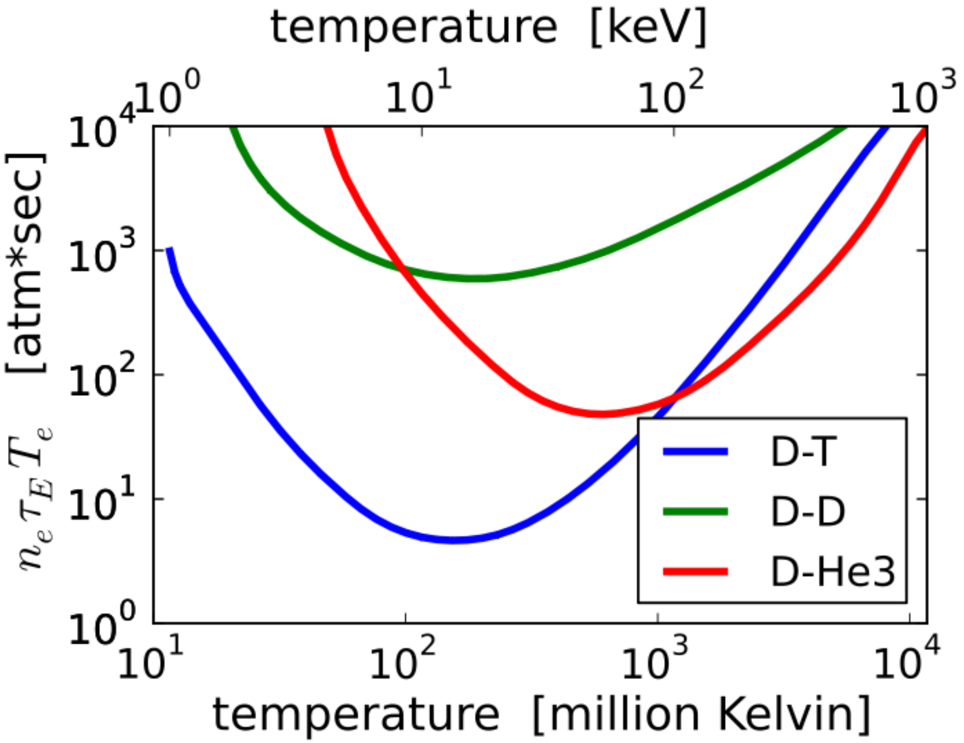
Plasma (ions & electrons) must be confined & heated

- to ignite and maintain burning plasma – use 3.5 MeV He+ ions from fusion reaction for self-heating
- Lawson ignition criterion – density (n) x time (τ) > min value

$n^*\tau > 2\times10^{20}\ m^{-3}$ sec

Fusion – Lawson Criterion

Lawson triple product



Lawson criterion

$n\,\tau_E > 12\,k_BT/\langle\sigma\upsilon\rangle\,E_{He}$

$> 2\times10^{20}$ s/m^3

Multiply Lawson Eqn x T; left side = pressure x time

Max $\langle\sigma\upsilon\rangle/T^2$ minimizes triple product $n^*T^*\tau_E$ $=p^*\tau_E$ for $Q=P_{out}/P_{in} = 1$

The Pathways

It’s all about heating and confinement of charged particles

- Theory – experiment – computer simulation – enabling technologies – now highly developed

- Mainline approaches – **magnetic** (low **n**, long τ) & **inertial** (high **n**, short τ) confinement

- Alternative approaches vary **n** and τ and confinement

- **But** – need more engineering innovation and scaling of manufacturing (tritium, materials, etc.)

Tokamak – Most Advanced Magnetic

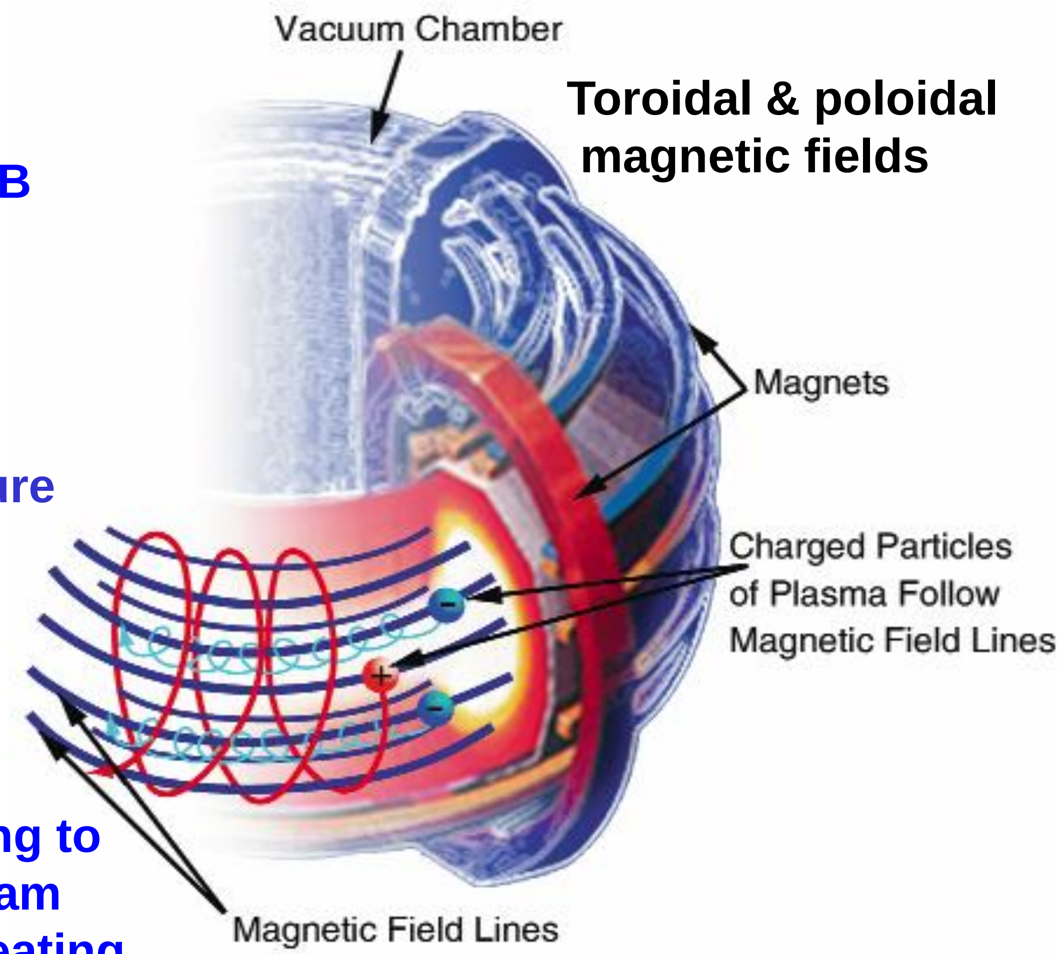
1950 – Sakharov & Tamm proposed Tokamak – add toroidal current –> poloidal B

Plasma drifts & instabilities limit confinement

β = plasma/magnetic pressure

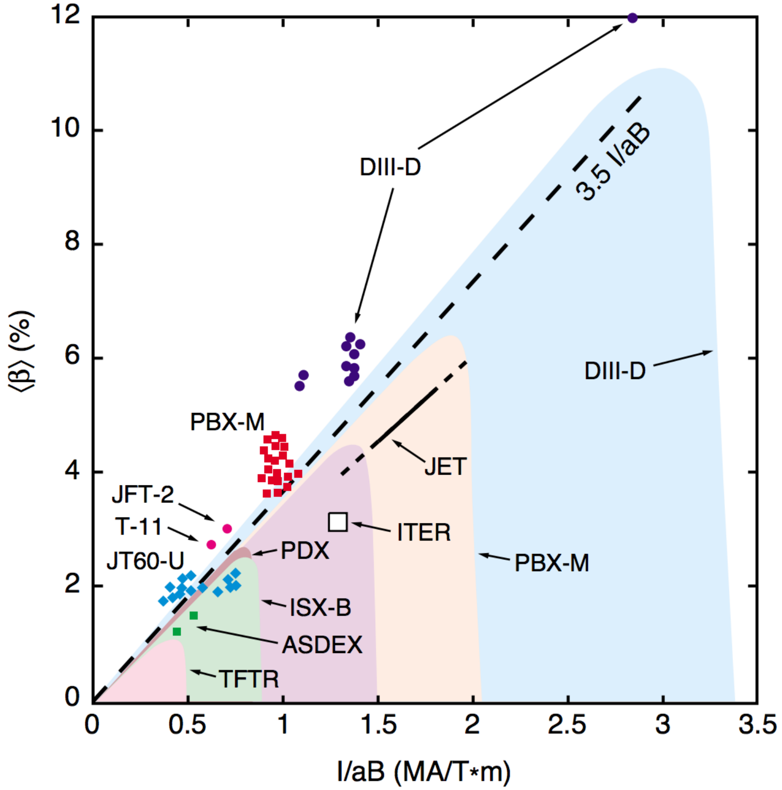
$\beta = \langle P \rangle / B^2 / 2\mu_o$

MFE requires auxiliary heating to achieve ignition – neutral beam injection; electromagnetic heating



Toroidal & poloidal magnetic fields

Tokamak – Instabilities Limit β



Confinement & power scaling

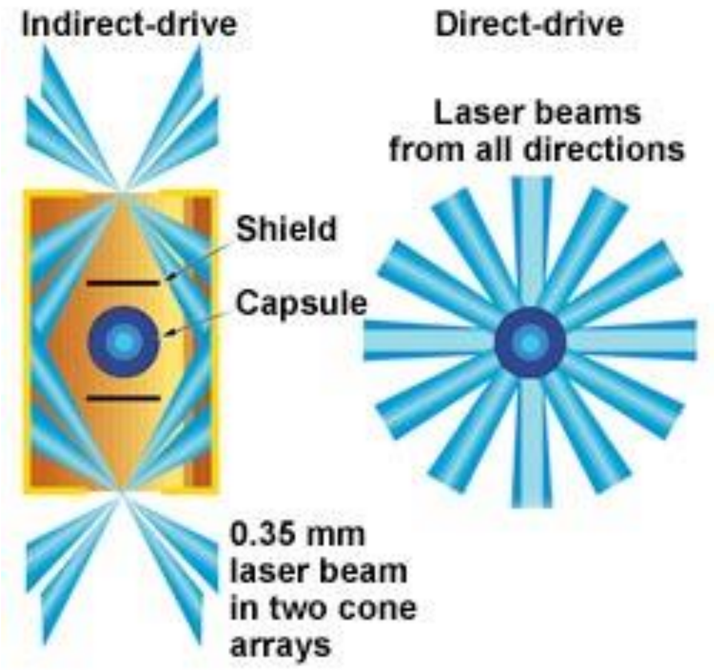
$$n^*T^*\tau_E \propto \beta_N B^3 R^{1.3}/q^2$$

$$P_{fus} \propto \beta^2_N B^4 R^3/(q^2 A^4)$$

Operating & stability limits: density, pressure, β,
MHD instabilities, bootstrap current – inter-related

Laser Driver – Most Advanced Inertial

Central Ignition



Requires fuel compression for net energy gain

Uses shaped laser pulse
Laser Intensity=500 TW/cm^2

$$\text{Yield} \sim P_{stag}^{2}\, T_{hs}^{2}\, V\tau$$

$$\sim u_{imp}^{7.7}$$

Hydrodynamic & laser/plasma instabilities limit compression

Progress

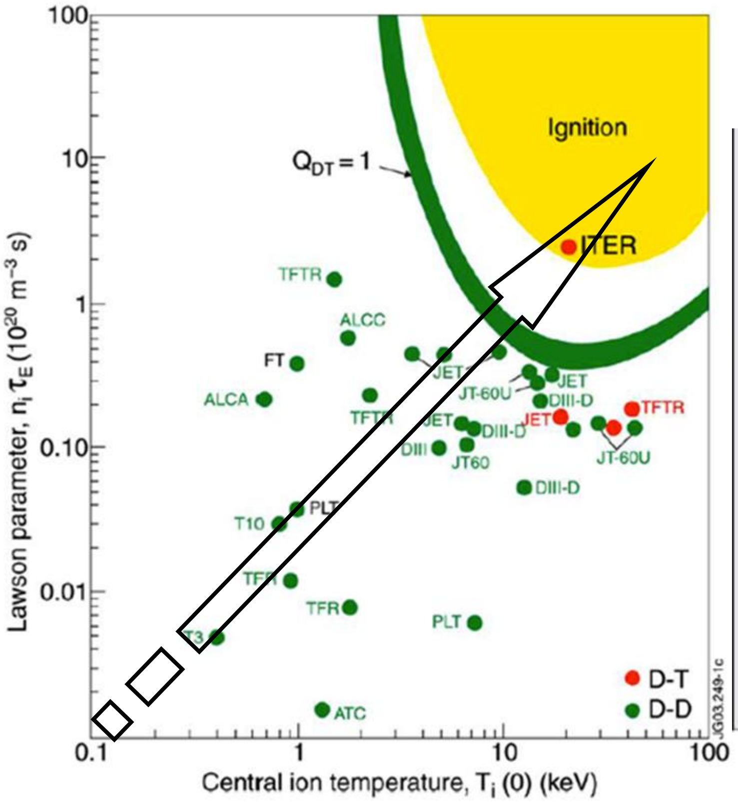
Magnetic & Inertial Fusion Energy

- Impressive scientific-technical progress – many devices built, studied; especially Tokamaks
- Progress has stimulated private sector involvement
- Technical issues remain, e.g. – materials, heating, plasma control (instabilities), diagnostics, robotics, cryogenics, tritium fuel breeding, pellet production

MFE-IFE – Recent Results

JET – latest result =59 MJ

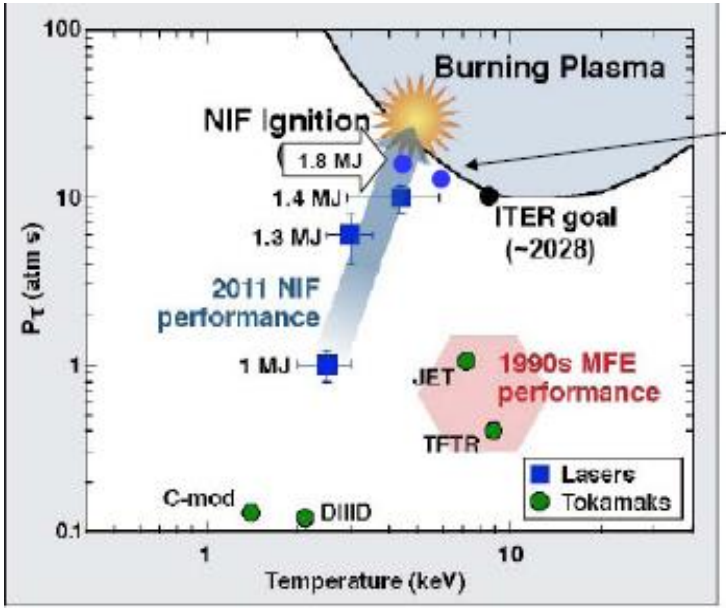
P_{th}=12 MW; Q=0.33; τ=5 s



Indirect drive at LLNL – near ignition

Latest result – E_{out} = 1.35 MJ; Q=0.7;

p*τ=22 atm-sec

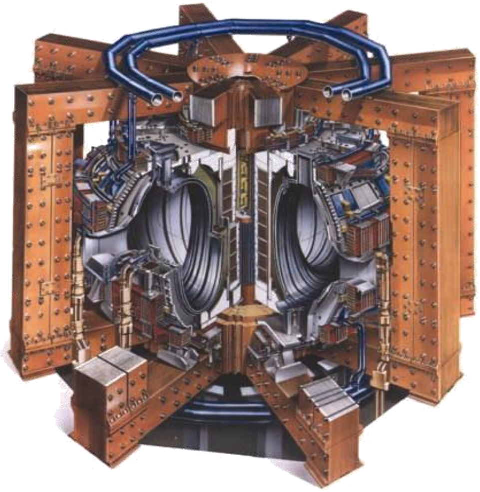


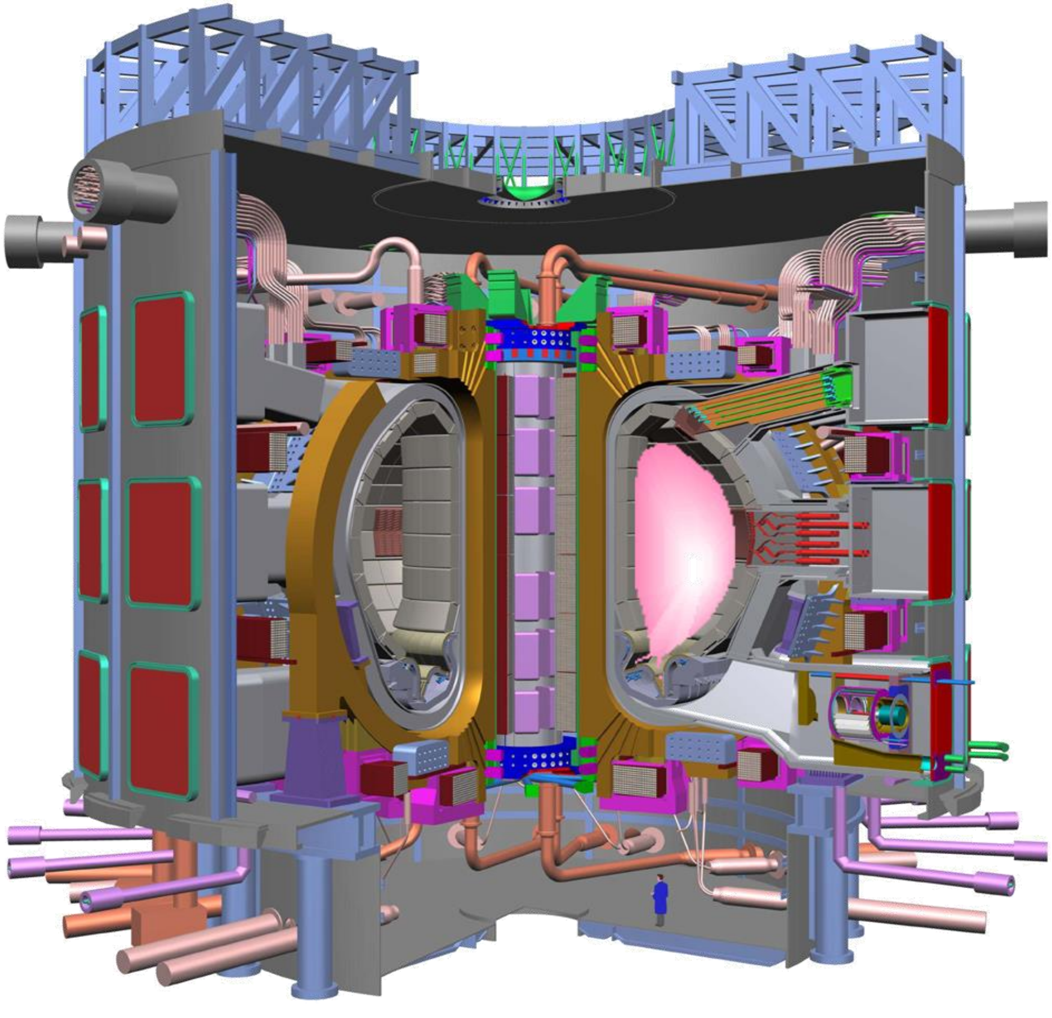
Earlier Results
E_{fusion}<0.25MJ

MFE – Scaling JET → ITER

ITER – 1,000 m^3
P = 500 MW; Q=10
τ=400 sec

JET – 100 m^3





Note: power Q refers to plasma heat output/input

IFE – Scaling to NIF & Beyond


National Ignition Facility

NIF – 192 beams
P = 500 TW
Q = 0.7
$p*\tau$ = 22 atm sec

IFE requires $\eta^{*}G>10$
η=laser efficiency
G=target gain

- **Advanced solid state lasers will reduce the footprint > 10 times (with high efficiency)**
- **KrF lasers offer an alternative driver technology with high efficiency and low cost potential**
- **Both SSL and KrF need demonstration of scaling to high energy**

Alternative & Advanced Concepts

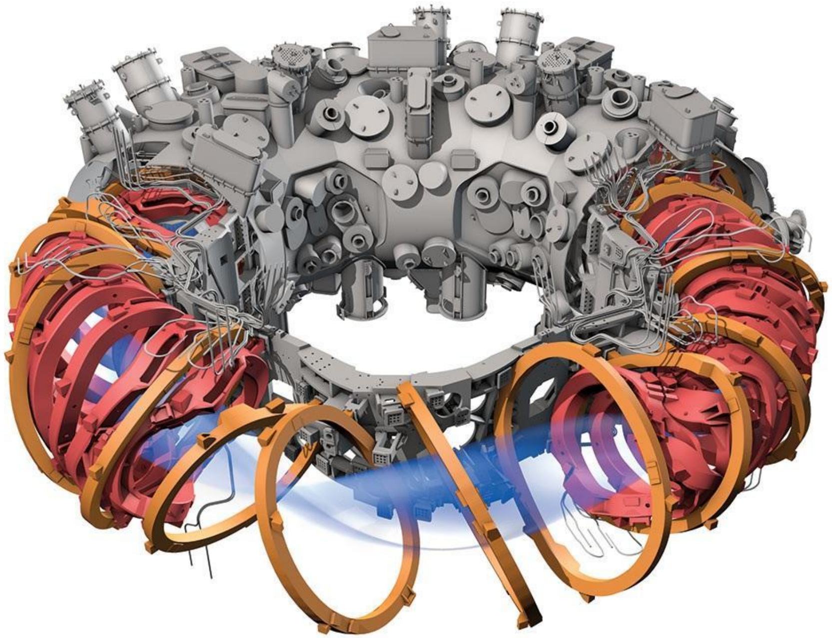
- Seek faster or more economically attractive route to commercial fusion - some 3 dozen alternatives have already emerged (magnetic, inertial, alternative)

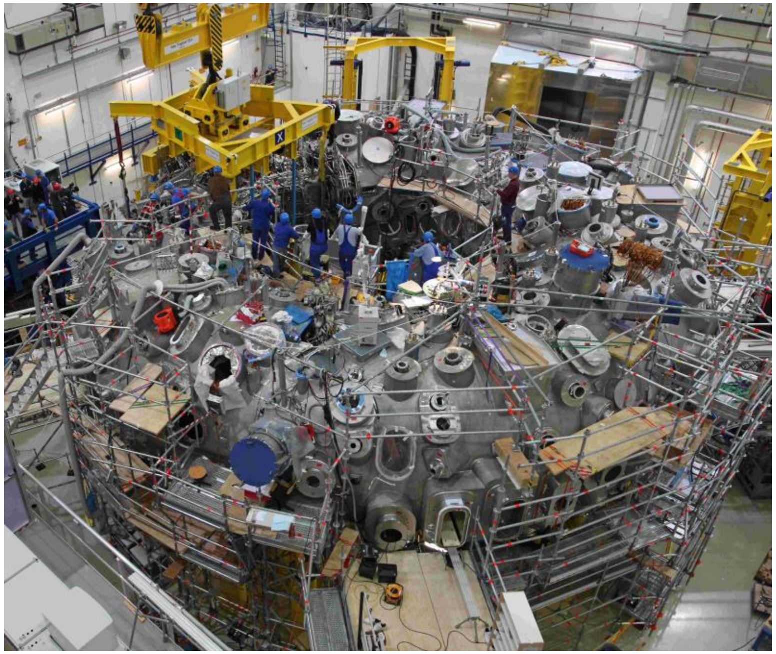
- Technical issues for all – materials, heating, plasma control (impurities & instabilities), diagnostics, cryogenics, robotics, tritium fuel breeding

- Major international programs underway to address technology issues

MFE – Stellarator

Steady-state alternative to Tokamak

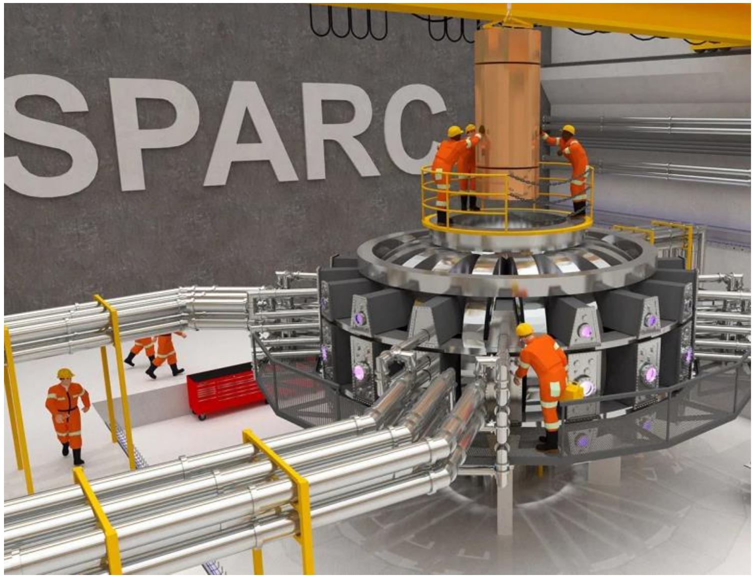




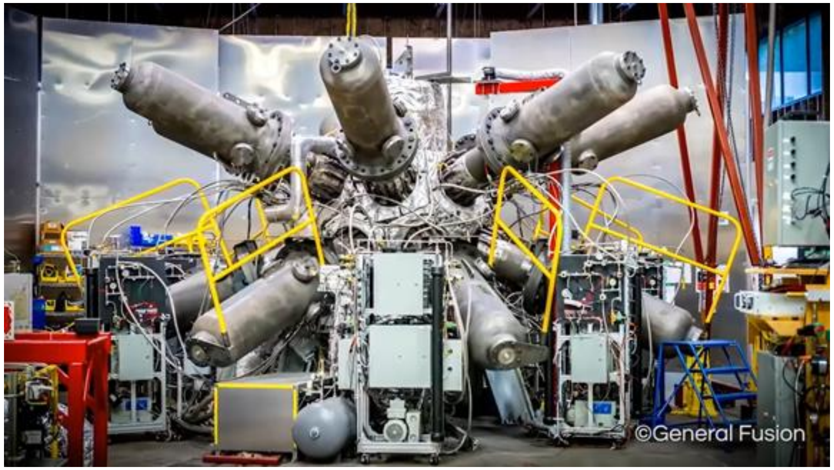
Wendelstein 7-X

Companies with fusion goals for 2030's

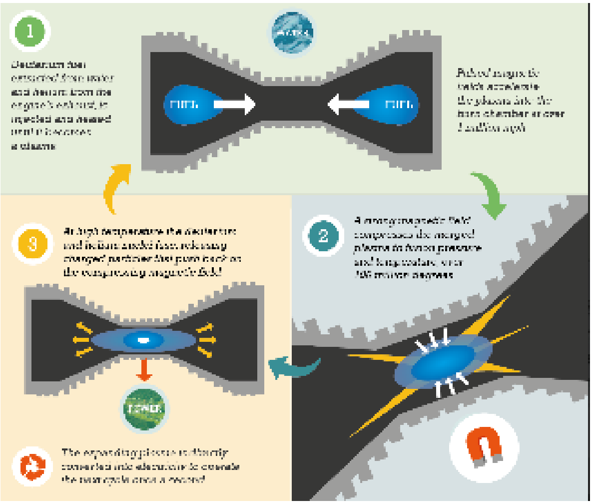
Commonwealth Fusion Systems



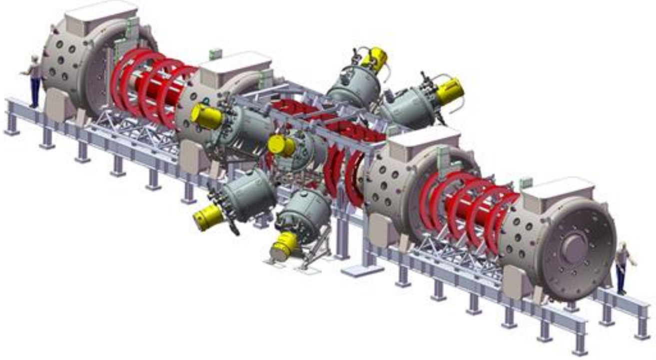
General Fusion


©General Fusion

Helion Energy

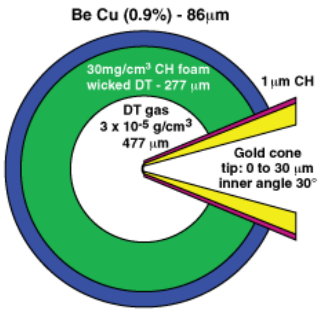


TAE Technology



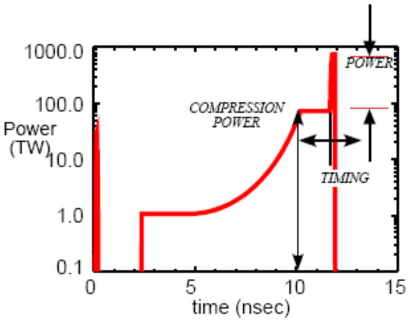
IFE – Employ Fast/Shock Ignition

Fast Ignition



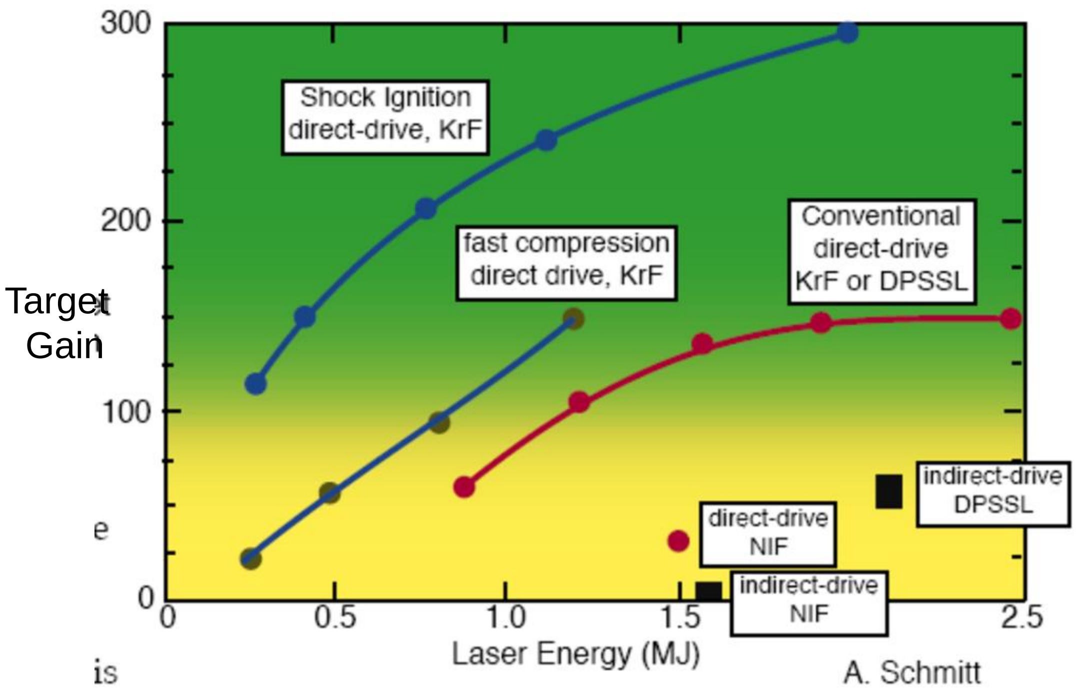
Uses PW, ps pulse
Laser Intensity=100 EW/cm^2

Shock Ignition



Uses high power peak at end of shaped pulse

Benefits



IFE requires η*G>10

MFE-IFE Power/Energy Systems

- Magnetic fusion (continuous, power delivery)

  ~1 W/m^3/kPa^2 ; pressure has been limited by B field to <10atm
  ~1 MW/m^3; implies large volume, low density
  ~1 MW/m^2 wall irradiance (radiation, charged particles, neutrons)

- Inertial fusion (pulsed, repetitive energy delivery)

  - small volume, high density ~10^{11} x higher; pressure >10^{11} atm
  - short burn time ~10^{-10} sec
  - operates like a “diesel engine”; implies injection of large # of fuel pellets

MFE-IFE Issues Comparison

- Magnetic fusion
  - lifetime of wall exposed to burning plasma
  - divertor lifetime under heat load
  - tritium fuel breeding
  - operational features & maintenance

- Inertial fusion
  - needs efficient, scalable high energy/average power lasers
  - needs high volume of targets daily – production & injection
  - potentially high efficiency & maintainability
    (tritium burnup – up to 10x better; maintenance accessibility

The Prospects

- MFE progress – Tokamak demo (or alternative?) to follow
- IFE progress – recent results promising (demo later)
- Private sector engagement will hasten development
- Financing (public-private) of multi-approaches underway
- Regulatory process not likely to inhibit progress
- Pilot plant possible by mid-2030’s – requires solution of technology issues (progressing worldwide)
- Energy & economic payoff will be transformative

Next Steps to Net Fusion Energy

- **Identify and build capability in advanced technologies requiring longer development time**
- **Expand university fusion science programs – to build capability and meet need for skilled people**
- **Encourage multi-path approaches – versatility essential since commercial success unpredictable**
- **Design and build systems to develop solutions for materials, T fuel breeding & handling, diagnostics, scaling of manufacturing, etc.**
- **Establish regulatory governance (especially regarding radioactivity) & support financing of fusion pilot plants**