Intro to Fusion

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COLUMBIA
PLASMA PHYSICS

fusion.columbia.edu

Thanks to Profs. Bhuvana Srinivasan and Felix Parra-Diaz for content !

My path so far:

- Studied physics & engineering
- Why Fusion? Seemed cool!
- Why US? More opportunities
- There is no master plan

... deep breath and take a step!
One step at a time, you'll go far

Presentation Scope

- Why bother ?
- What conditions are required ?
- What are the approaches ?
- Where have we been ?
- Where are we going ?

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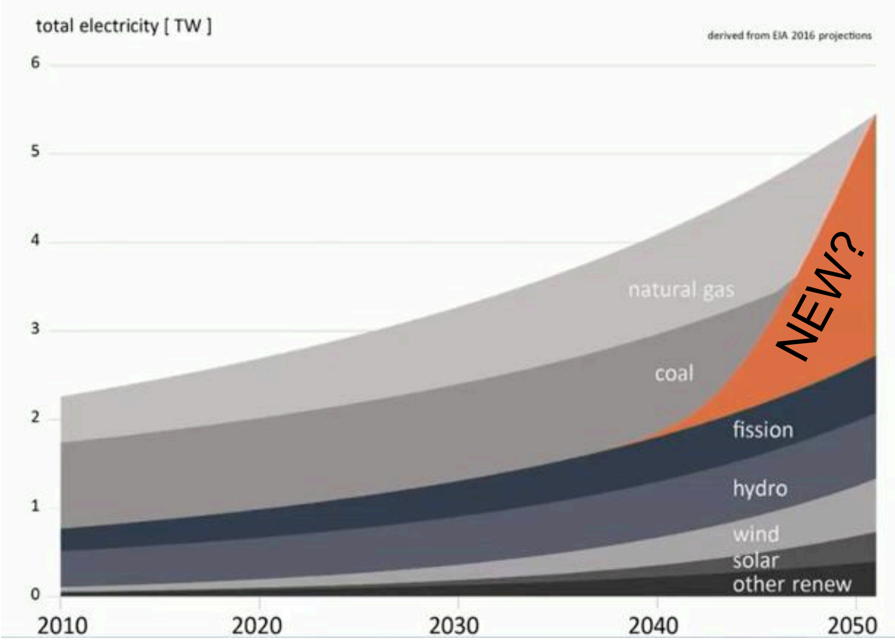
Ask AI: “holy grail of energy”

Societal Need for Energy Transition

- Transition to low-carbon generation for climate
- Independence from petro-states for national security
- Physics & Engineering needed to solve the problem!



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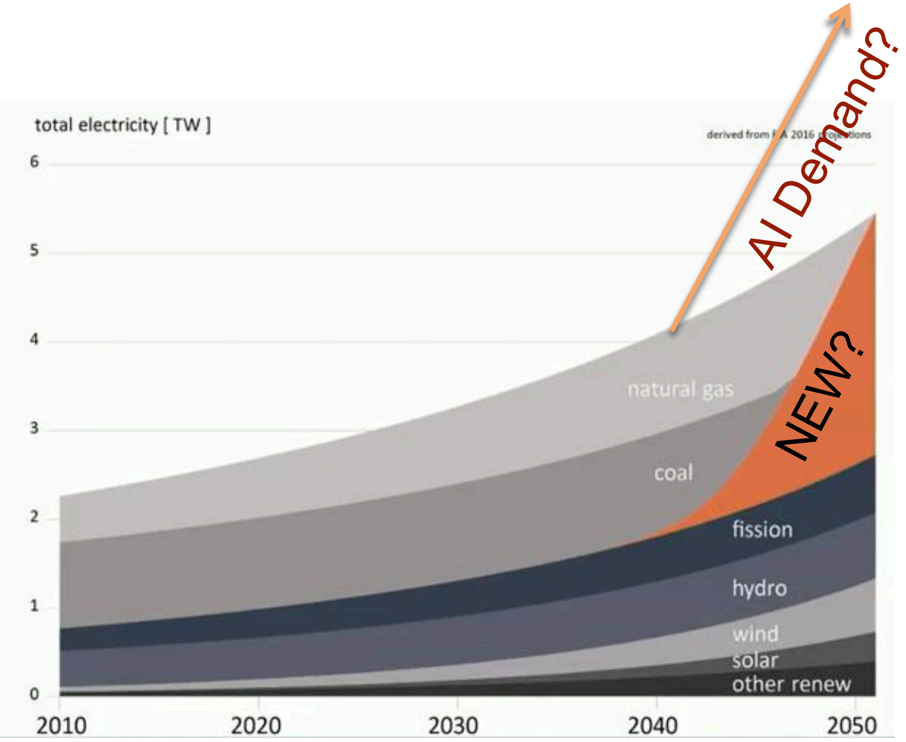
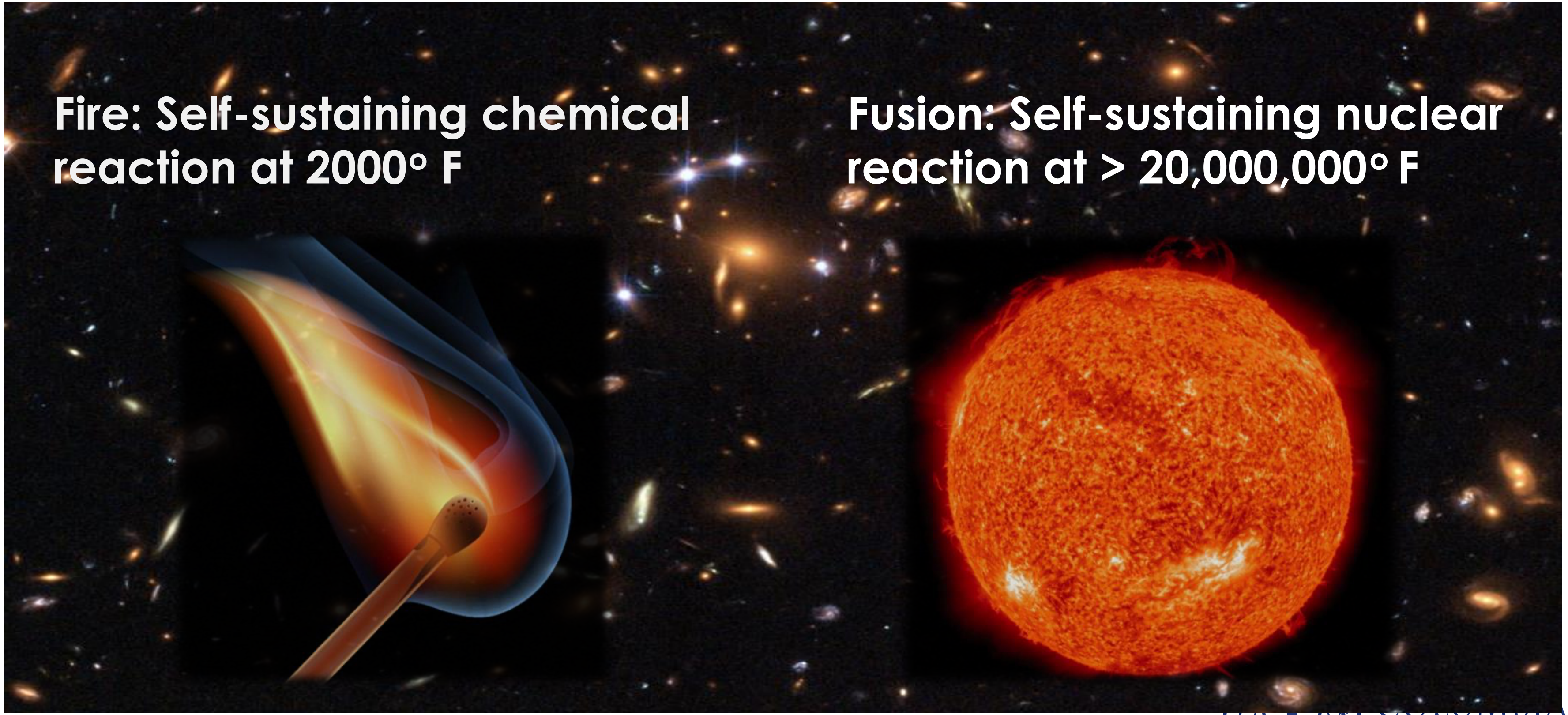


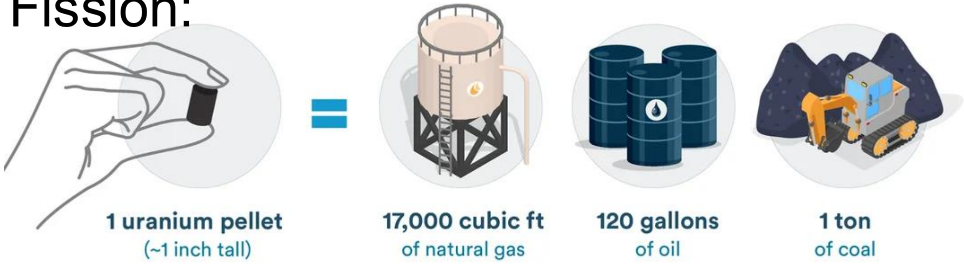
Significant Energy Exists in the Nucleus



Significantly Less Fuel Required

- Per reaction, get ~ 1 "MeV"
- ~Million times more energy than a chemical reaction like burning fossil fuels

Fission:

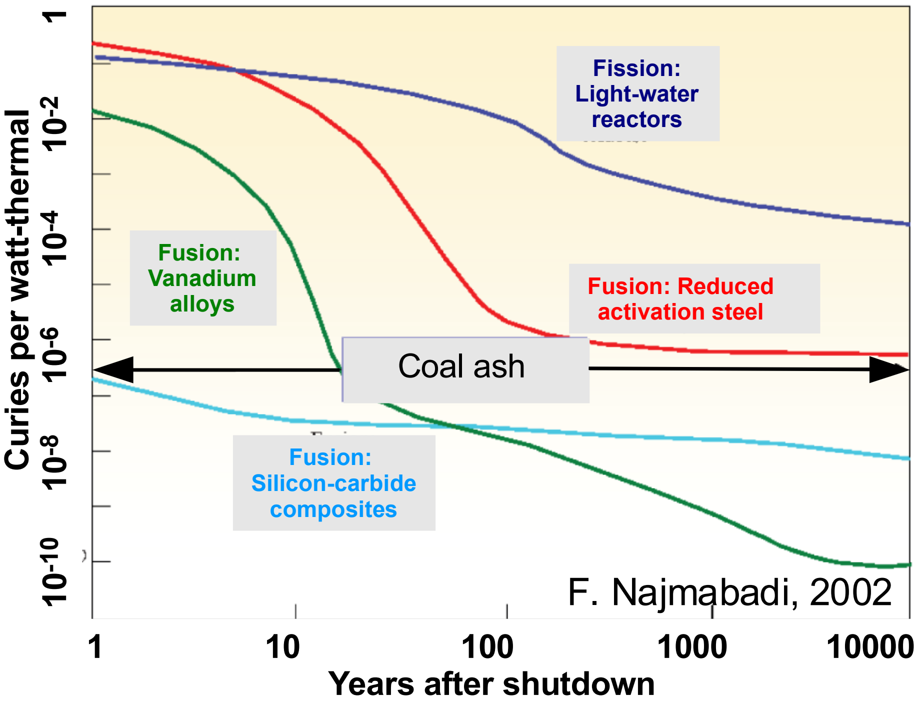


Source: General Fusion

Significantly Less Radioactive By-Products

- All nuclear power is radioactive during production
- Fusion's radioactivity is <u>not long lived</u>
- Disposal in existing facilities for generated low-level waste

Radioactive decay times of fission and fusion structural materials after shutdown [2]



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Why is Fusion the "Holy Grail" of Energy?

- **Clean**

  no emissions, no long-lived,
  high-level radioactive waste

- **Firm**

  dispatchable power on call, when needed

- **Safe**

  opposite process of fission, no risk of meltdown

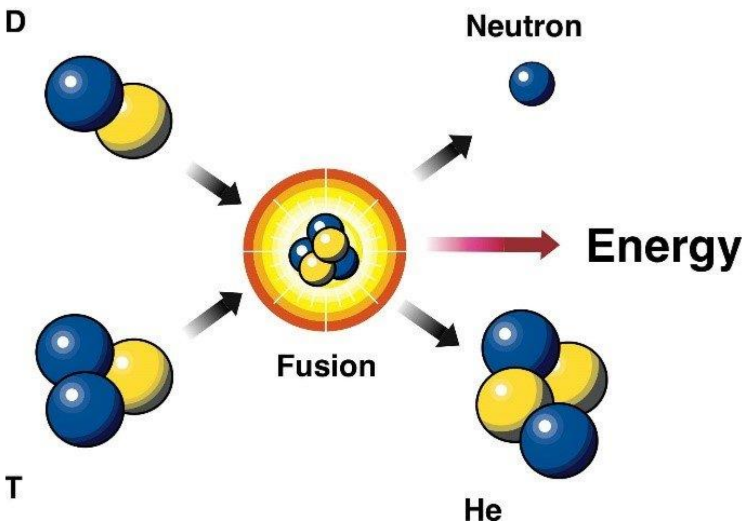
- **Scalable**

  affordable, modular, capable of siting near loads

- **Secure**

  no geopolitically fraught supply chain,
  all fuel can be procured up front

Hydrogen Isotopes



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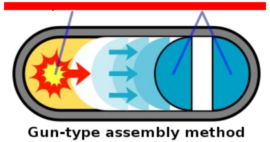
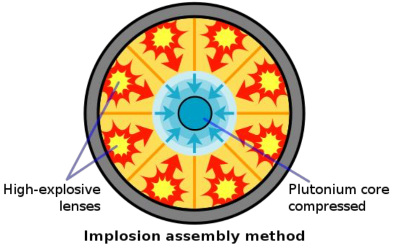
Controlled Fusion is the Missing Quadrant

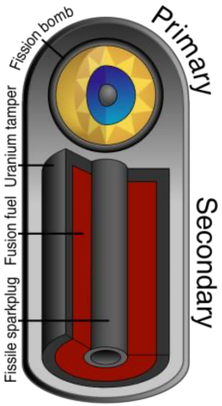
Uncontrolled

Fission

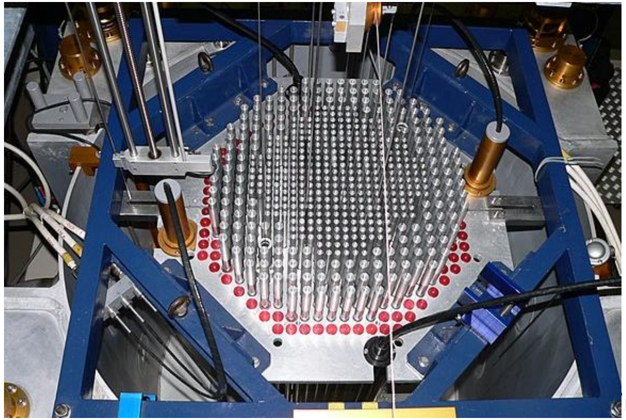


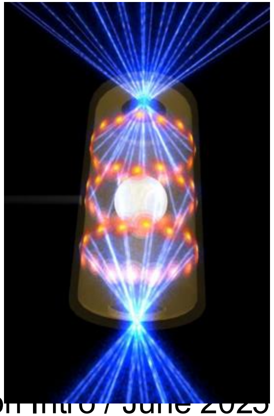


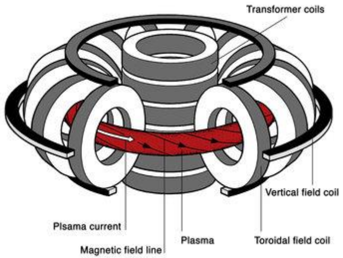
Fusion



Controlled







? ?

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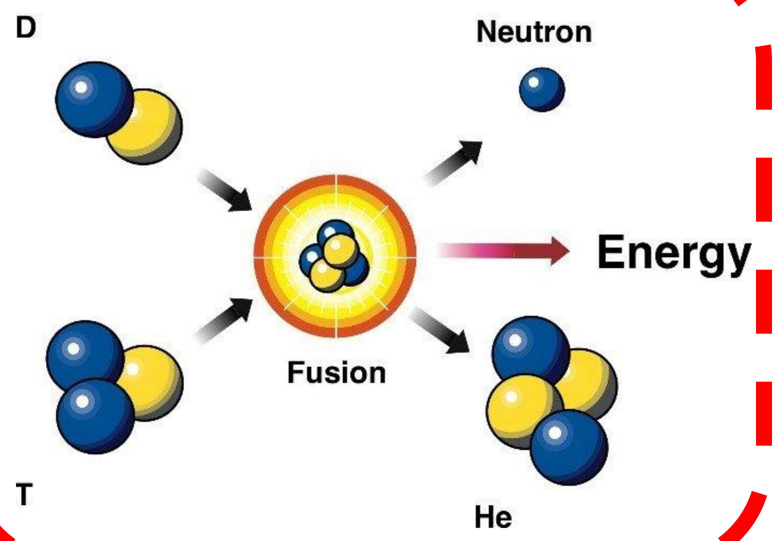
Historic Atomic Energy Development

- 1945 → First fission bomb test (w/ Manhattan Project)
- 1952 → First fusion bomb (H-bomb) test
- 1952 → “Nautilus” first fission powered submarine
- 1958 → “Shippingport” first fission commercial *demo plant*

? Why didn’t we get controlled fusion shortly after this era ?

Why has Fusion ***always been*** the "Holy Grail" of Energy?

? Fusion Device ?



<u>Challenges → It's really hard !</u>

- Controlling high-temperature plasma needed for reaction
- Overcoming high capital cost requirements for prototypes
- More R&D needed for several device sub-components

<u>! We'll go deeper for rest of the talk (and course) !</u>

Presentation Scope

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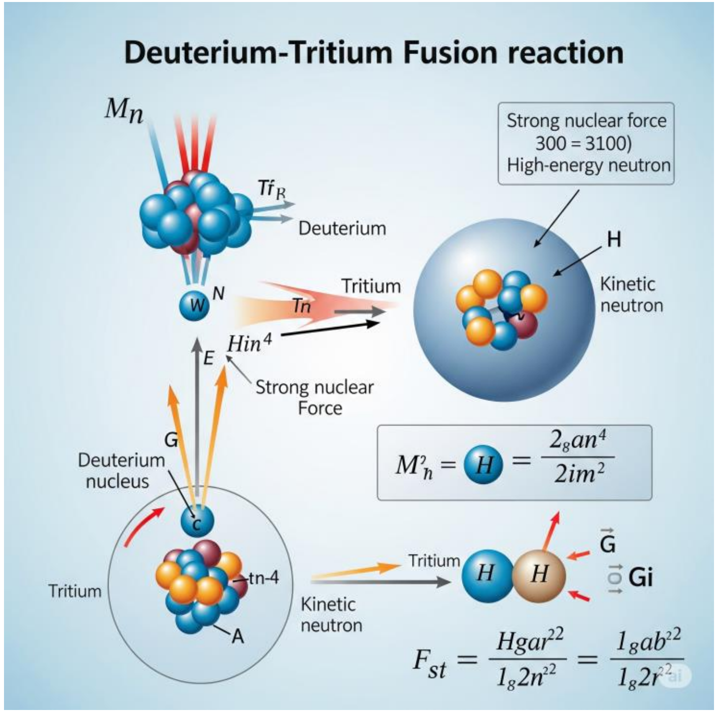

Ask AI: "DT Fusion Reaction"

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High temp. and pressure needed: Why ?

Let's learn about some concepts to help understand if fusion reaction produces enough energy + has high reactivity:

1. Coulomb forces versus nuclear forces

2. Gamow peak

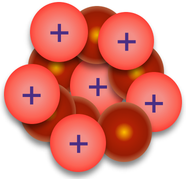
3. Cross-sections for the different reactions

High temp. and pressure needed: Why ?

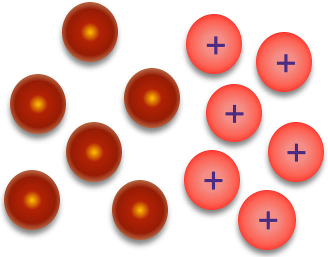
Let’s learn about some concepts to help understand if fusion reaction produces enough energy + has high reactivity:

1. **Coulomb forces versus nuclear forces**
2. Gamow peak
3. Cross-sections for the different reactions

Nuclear binding energy sets available reaction energy



+ Binding energy =



Nucleus

Nucleons

Protons and neutrons, i.e. nucleons, held together in nucleus by strong nuclear force

The mass of individual nucleons > mass of the nucleus

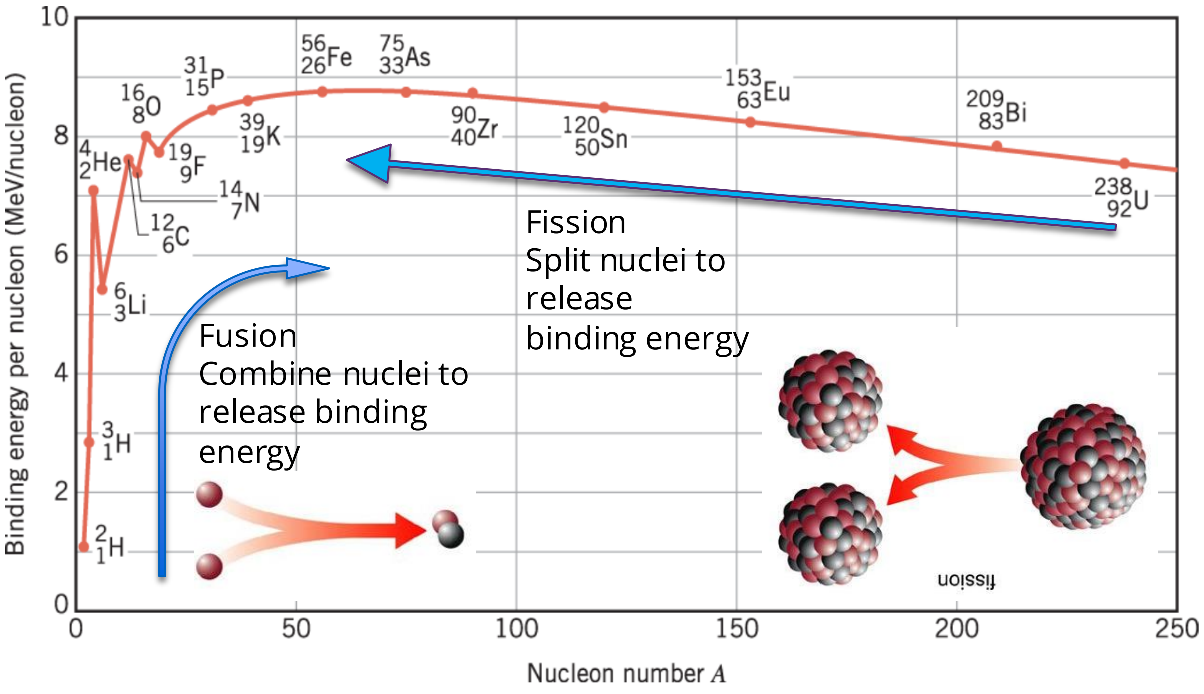
$$E = mc^2$$

$$\Delta E = \Delta mc^2$$

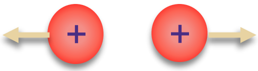
Attractive strong nuclear force holds protons and neutrons together in a nucleus. Binding energy needed to pull them apart.

The binding energy of the nucleus is directly related to the amount of energy released in a fusion reaction or in a fission reaction

Nuclear binding energy released per nucleon



Like charges repel – Coulomb forces provide a potential barrier to overcome



$$F \propto \frac{q_1 q_2}{r^2} \qquad U \propto \frac{q_1 q_2}{r}$$

- Note that an atom ~ 1 Angstrom ~ 10^{-10} m
- Attractive nuclear forces ~ 10^{-15} m
- For larger distances, need to overcome long-range repulsive Coulomb forces before attractive strong nuclear forces dominate
- Requires input energy to ions to overcome the Coulomb barrier

- This input energy must be practically achievable → rules out most fusion reactions in the periodic table

High temp. and pressure needed: Why ?

Let's learn about some concepts to help understand if fusion reaction produces enough energy + has high reactivity:

1. Coulomb forces versus nuclear forces

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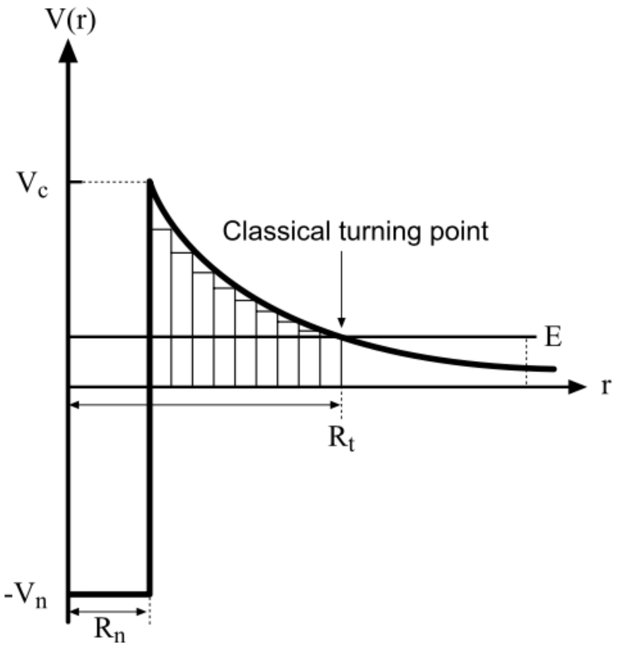
3. Cross-sections for the different reactions

Quantum mechanics: finite probability for an ion to penetrate the Coulomb barrier

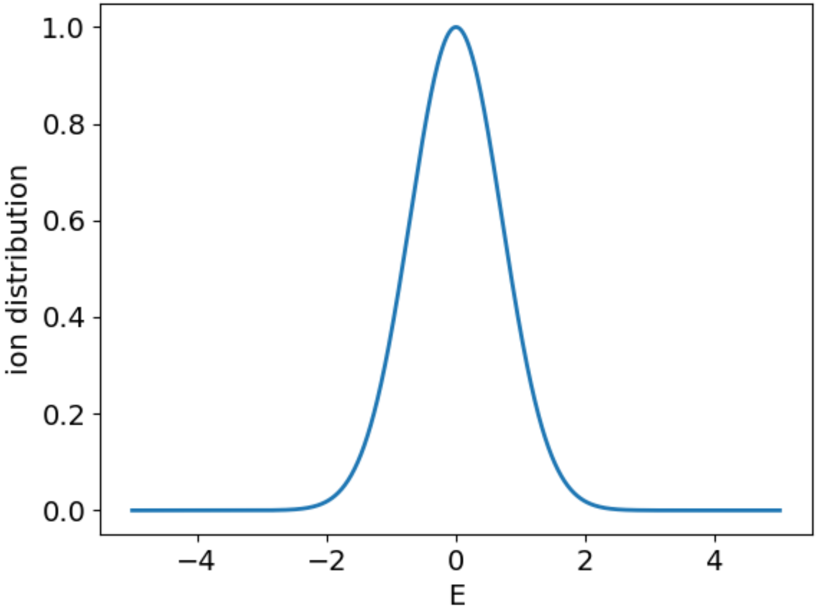


Credit: José, Stellar Explosions (2016)

- Quantum tunneling through which the ions penetrate the Coulomb barrier [Gamow (1928)]
- Penetration probability comes from the time-dependent Schrödinger equation, i.e. the wave equation
- This probability is given by an exponential, known as the Gamow factor

Quantum mechanics: finite probability for an ion to penetrate the Coulomb barrier

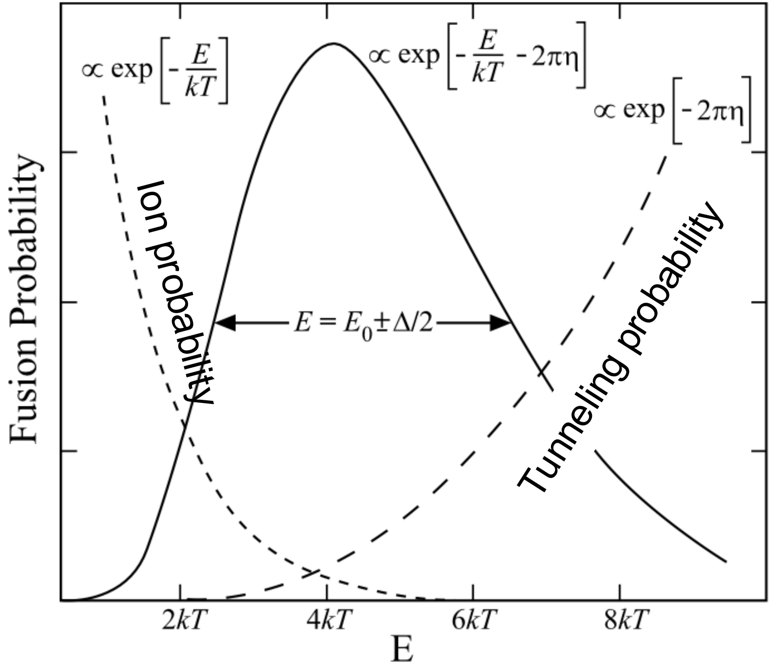
Probability



Particle energy

- Most plasma is assumed to be distributed as a Gaussian with respect to energies, specifically a Maxwellian distribution
- This Maxwellian distribution is also given by an exponential function

Quantum mechanics: finite probability for an ion to penetrate the Coulomb barrier



Credit: José, Stellar Explosions (2016)

- The product of the two exponentials: the Maxwellian distribution and the tunneling probability → provides the Gamow peak
- Specifies the energy range at which a specific nuclear reaction occurs for a given temperature
- Tunneling probability also relates to the concept of cross section

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High temp. and pressure needed: Why ?

Let’s learn about some concepts to help understand if fusion reaction produces enough energy + has high reactivity:

1. Coulomb forces versus nuclear forces

2. Gamow peak

3. **Cross-sections for the different reactions**

What are some viable fusion reactions?

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He}\ (3.52\ \mathrm{MeV}) + \mathrm{n}\ (14.06\ \mathrm{MeV})$$

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}\ (1.01\ \mathrm{MeV}) + \mathrm{p}\ (3.02\ \mathrm{MeV})$$

$$\rightarrow {}^{3}\mathrm{He}\ (0.82\ \mathrm{MeV}) + \mathrm{n}\ (2.45\ \mathrm{MeV})$$

$$\mathrm{D} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He}\ (3.6\ \mathrm{MeV}) + p\ (14.7\ \mathrm{MeV})$$

$$\mathrm{p} + {}^{11}\mathrm{B} \rightarrow 3\ {}^{3}\mathrm{He} + 8.7\ \mathrm{MeV}$$

These are the only fusion fuels that are theoretically feasible for exploitation

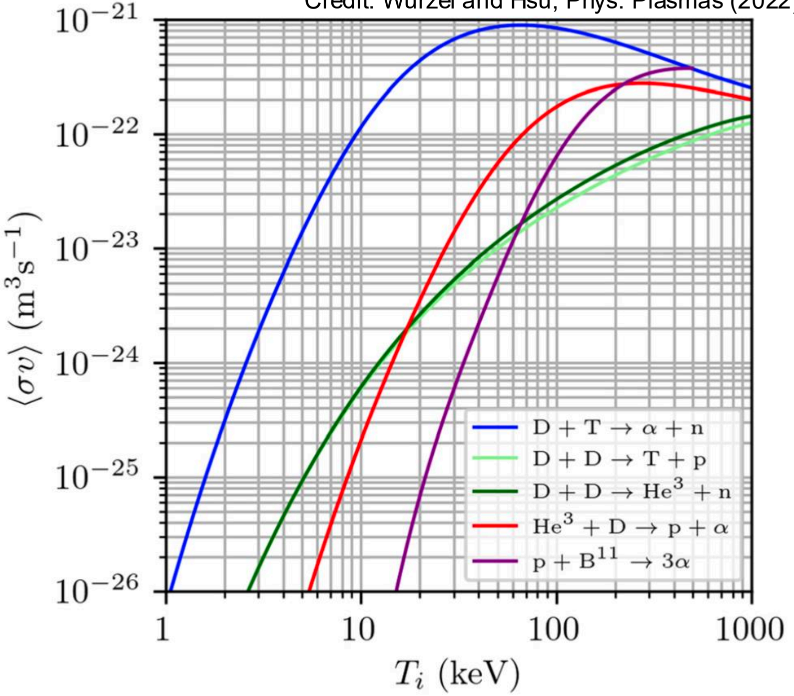
Note these reactions are aneutronic and highly desirable, but more challenging, we'll see why.

Remember that 1 MeV = 1.6 x 10^{-13} J

Each fusion reaction has a collision cross-section that is a function of energy

- Collision **cross-section**, ***σ*** [m²], is the effective area "seen" by colliding ions
- Each Coulomb collision has a **relative velocity**, **v** [m/s], between the colliding ions
- Want to maximize the **fusion reaction rate**, given by < ***σ*** **v** > (function of temperature, comes from the Gamow peak)
- The D-T reaction has the highest reaction rate and at the lowest temperature
  - > 20 keV = 200 million degrees!
  - > Temp at core of the sun ~ 15 million degrees (but much higher density)

Credit: Wurzel and Hsu, Phys. Plasmas (2022)



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Each fusion reaction has a collision cross-... energy

- Collision **cro**... effective are...
- Each Coulon... **velocity**, **v** [...
- Want to max... given by < σ... comes from...
- The D-T reac... rate and at the...
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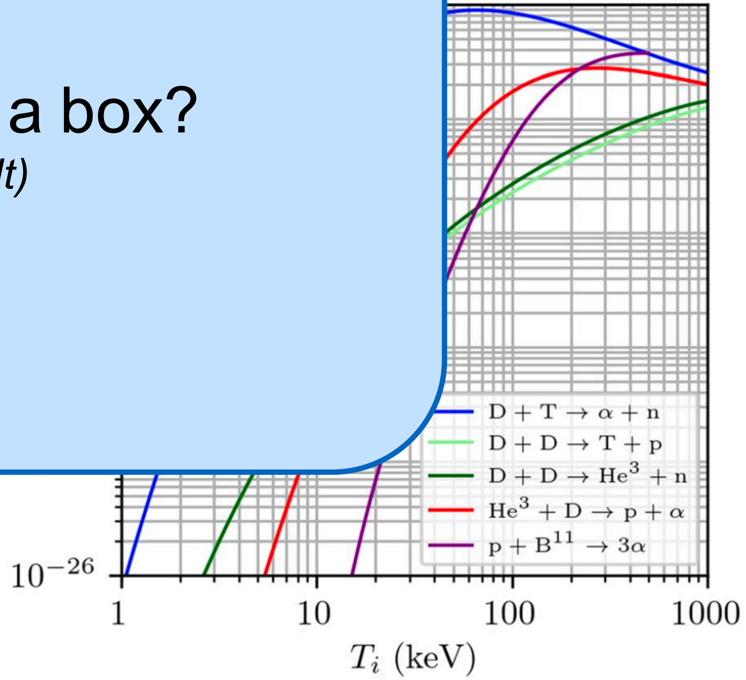

How to do this in a box?

(that doesn't melt)

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Metrics to Measure Fusion Proximity?

<u>Things we want:</u>

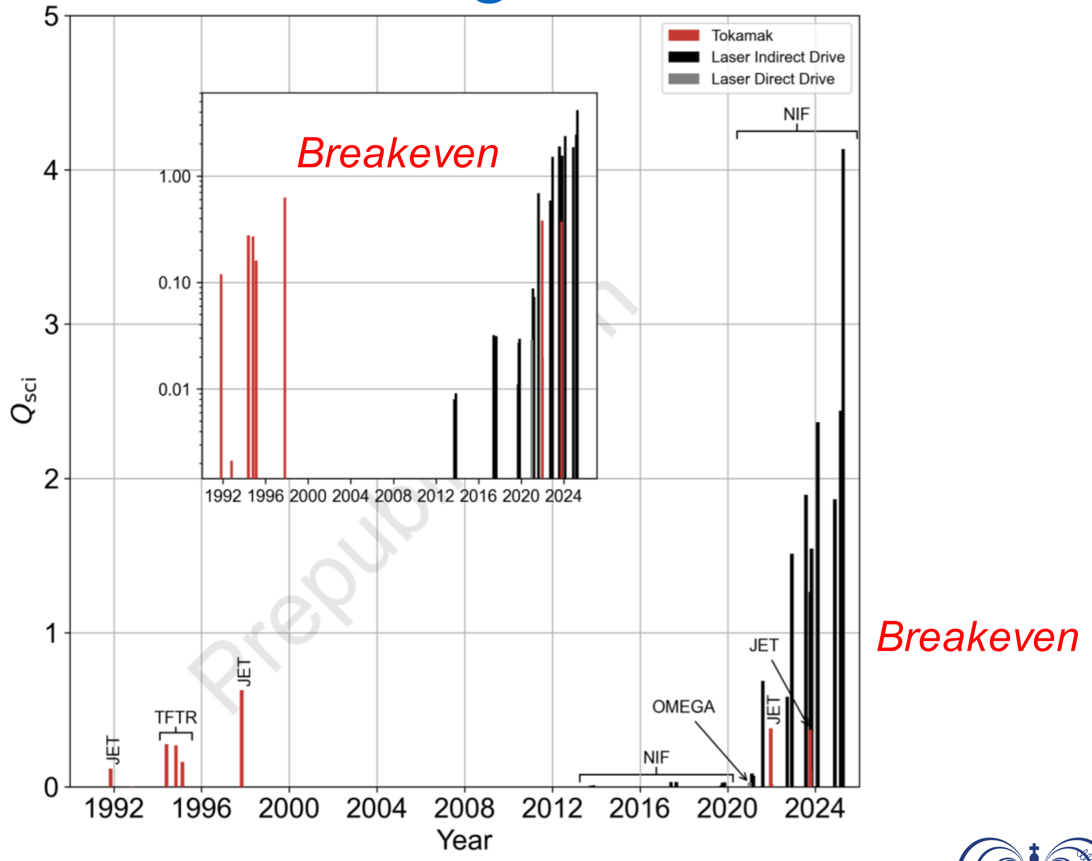
- "Ignition" → Energy to sustain plasma fully from fusion reactions
- "Burning Plasma" → Fusion reactions dominate energy balance
- "Breakeven" → Energy out from fusion exceeds energy in
- Measured via Fusion Gain "**Q**" == Energy Out / Energy In

Metrics to Measure Fusion Proximity?

Things we want:

- “Ignition” → Energy to sustain plasma fully from fusion reactions
  Q=infinity
- “Burning Plasma” → Fusion reactions dominate energy balance
  Q=5 or 10 *(depends on details)*
- “Breakeven” → Energy out from fusion exceeds energy in
  Q=1
- Measured via Fusion Gain “**Q**” == Energy Out / Energy In

Fusion Gain Progress over Time



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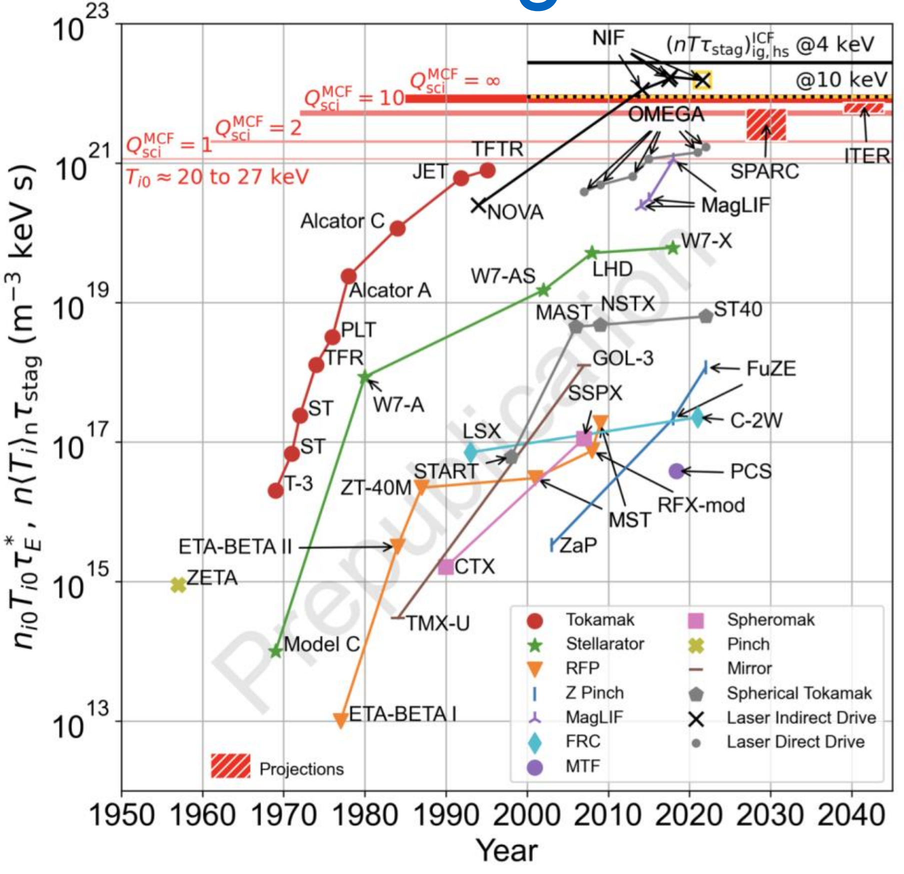
Metrics to Measure Fusion Proximity?

<u>More scientific</u>

- Triple product: Density * Temperature * Confinement Time
  - also can be considered as pressure [atm] * confinement time [s]
  - Magic number about 8 atm-s (@ ~10 keV)
- Confinement time: ~ time takes un-driven plasma to wither away
- Lawson Criterion: similar metric, just removing temperature

Triple Product Progress over Time



Caveat: Temperature cannot be traded off with the other two quantities and should be carefully scrutinized when evaluating any triple-product claim.

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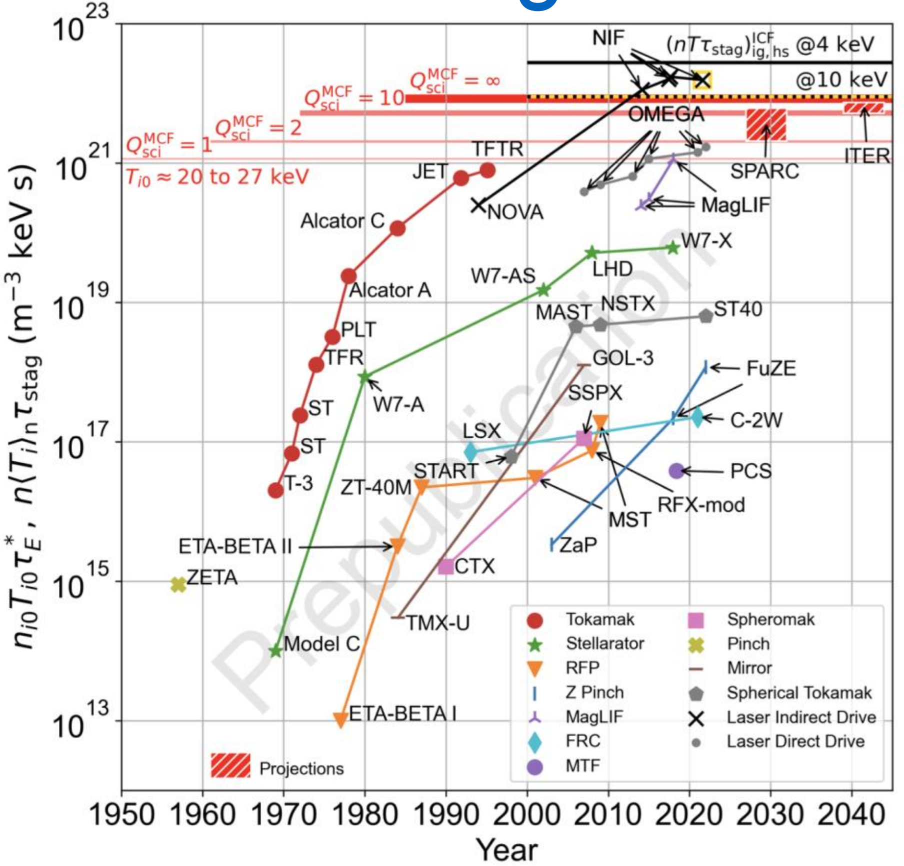
Triple Product Progress over Time



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Time to talk about:
- Concepts
- History

Presentation Scope

- Why bother ?
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- **What are the approaches ?**
- Where have we been ?
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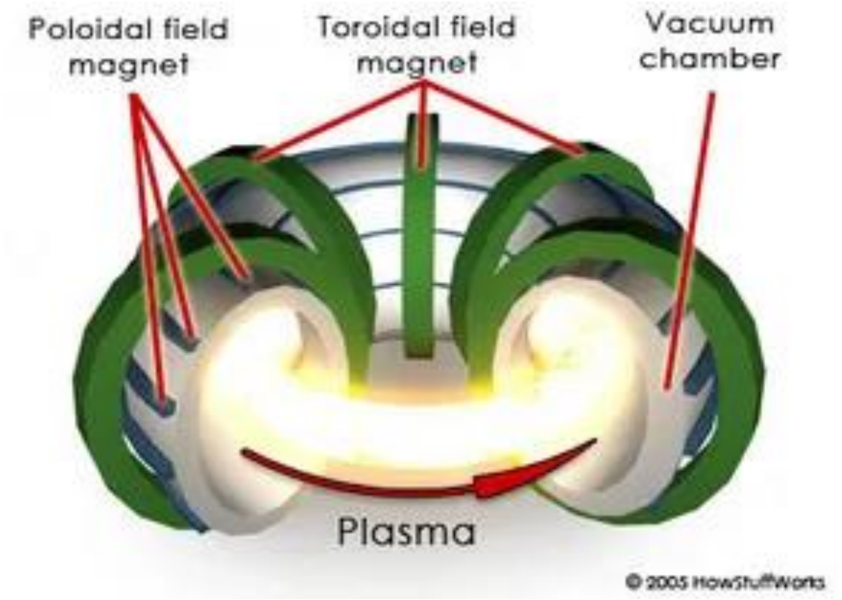
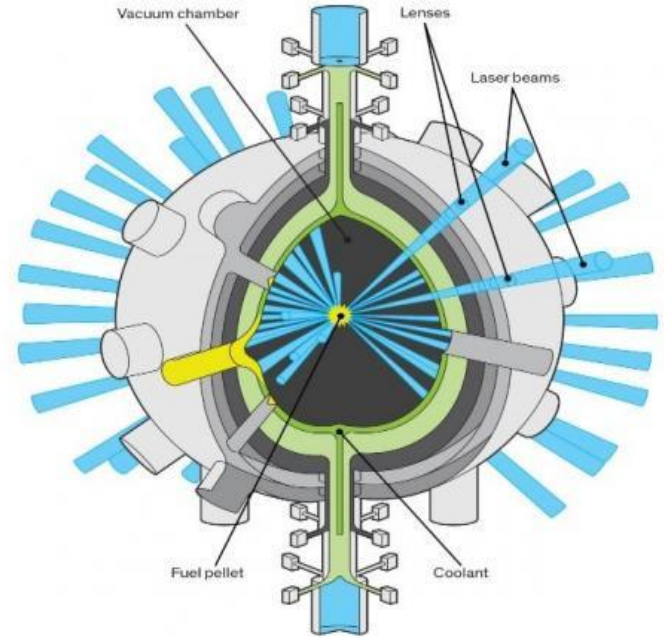
Ask AI: "fusion machine"

Two Approaches to Controlled Fusion

- Magnetic Fusion



- Inertial Fusion (ie, lasers)



+ the sun works, too! (via gravity)

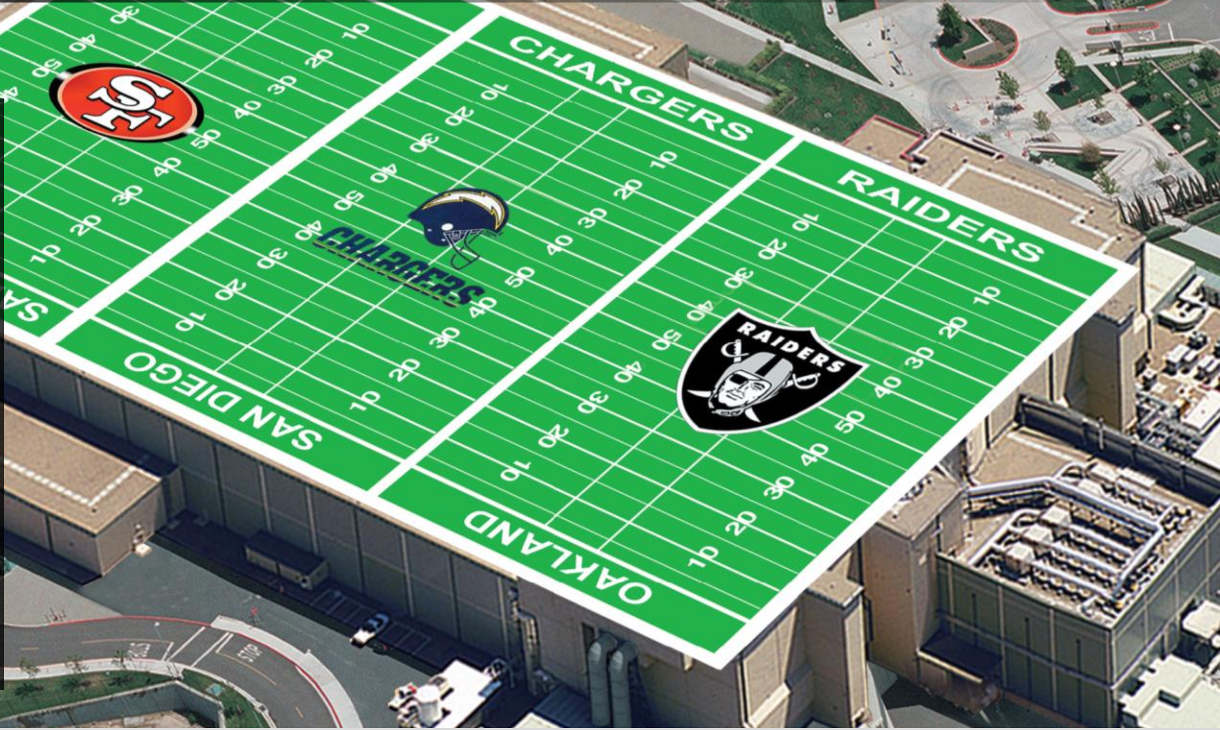
At the National Ignition Facility (NIF) in California there exists a miniature sun

Courtesy:
Lawrence Livermore National Laboratory

National Nuclear Security Administration

NIF is the world’s largest and most energetic laser for study of extreme conditions of fusion and high energy density science

- 192 Beams
- Energy: 2.2 MJ
- Power: 500 TW
  (1,000x power of US electrical grid)
- Frequency tripled Nd glass
- Wavelength: 351 nm
- Pulse length: ~10-25 ns



Courtesy:
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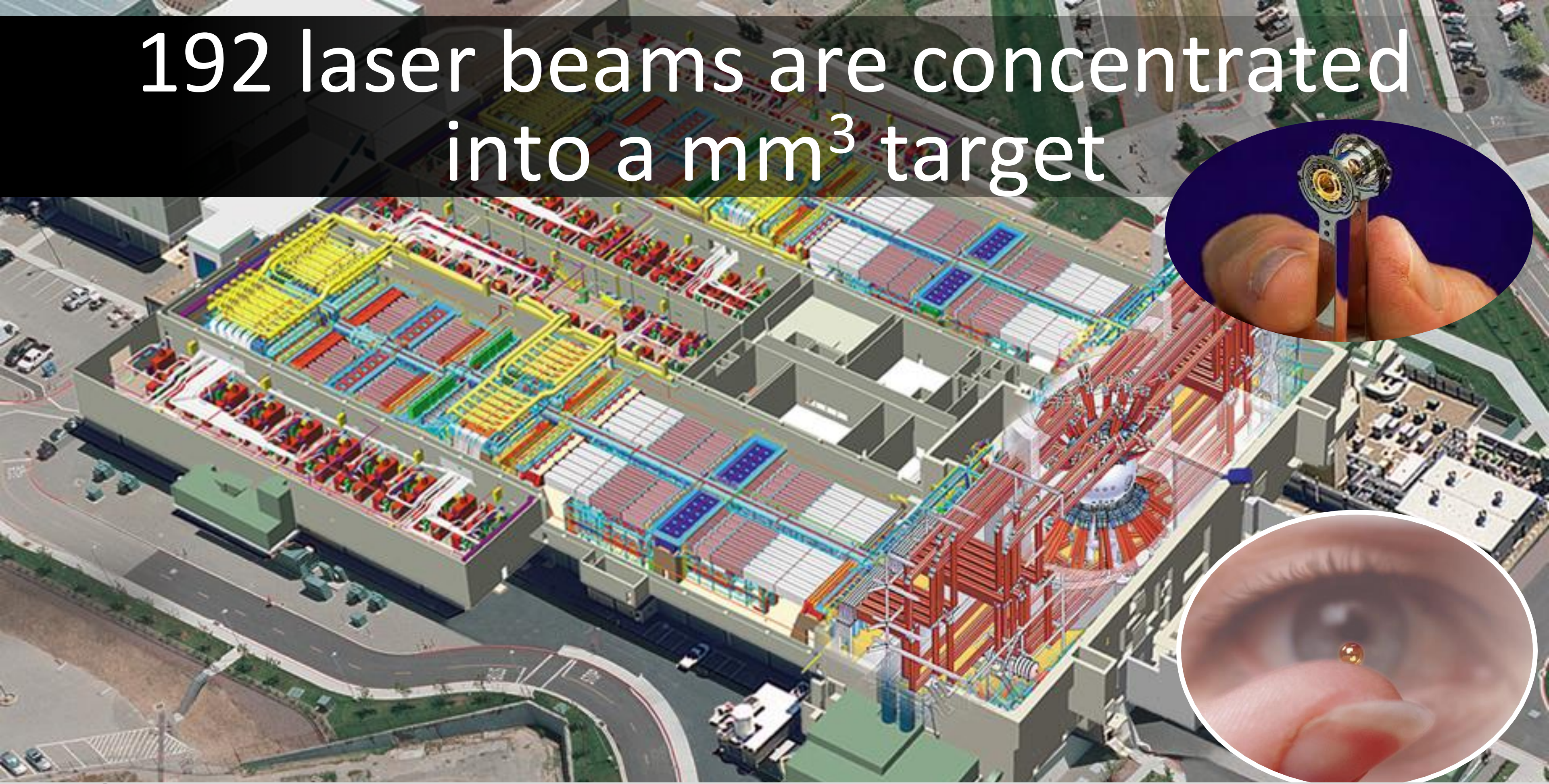
National Nuclear Security Administration

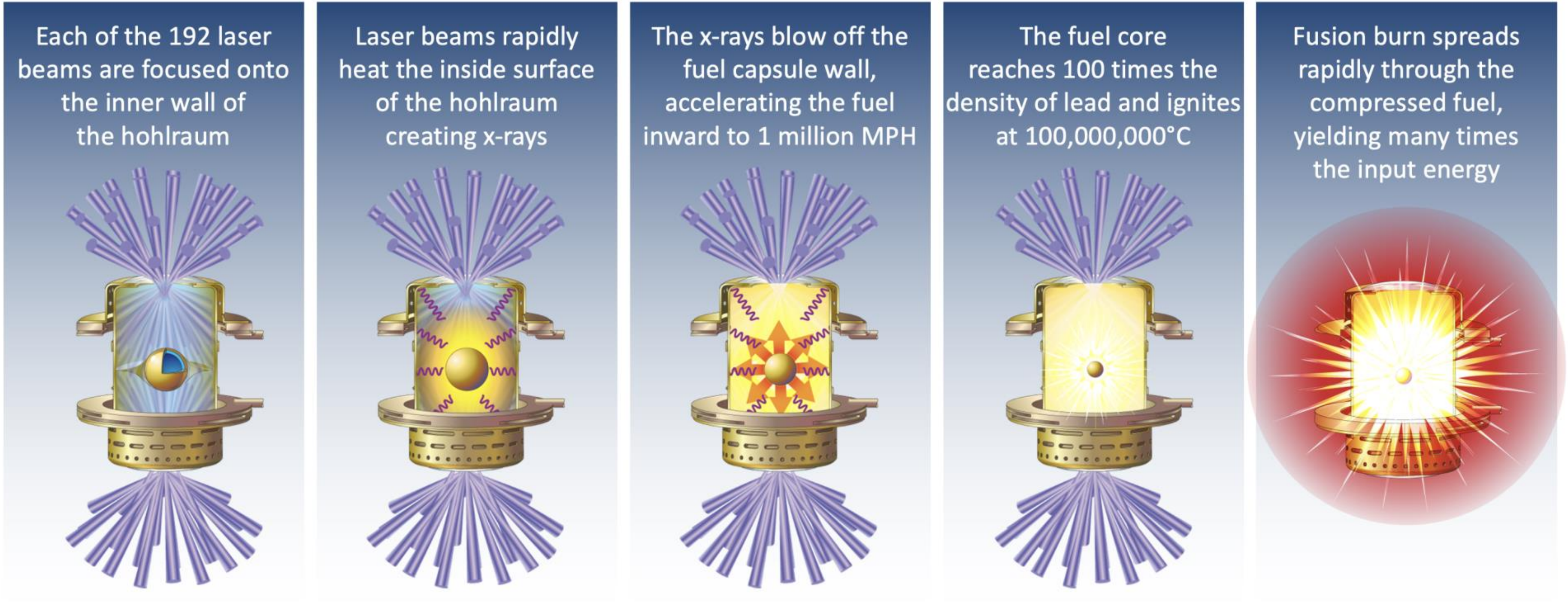
192 laser beams are concentrated into a mm^3 target



Courtesy:
Lawrence Livermore National Laboratory

National Nuclear Security Administration

Process of laser-driven fusion at the NIF



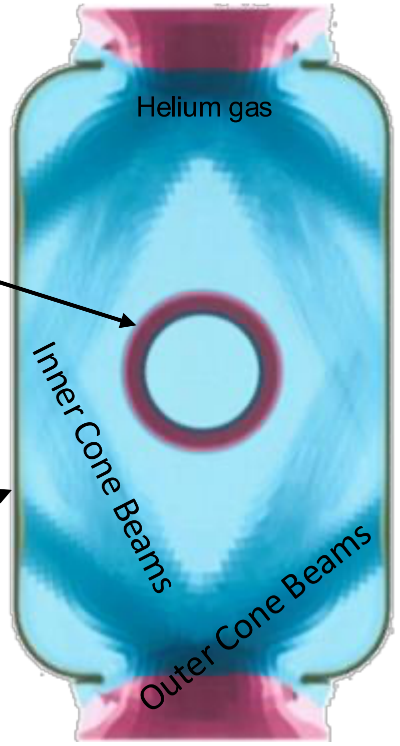
With this approach, NIF achieved alpha heating, burning plasma, and ignition (Q_{target} or Q_{sci}>1)

Courtesy:

Lawrence Livermore National Laboratory

National Nuclear Security Administration

Plasma Energy Gain at NIF



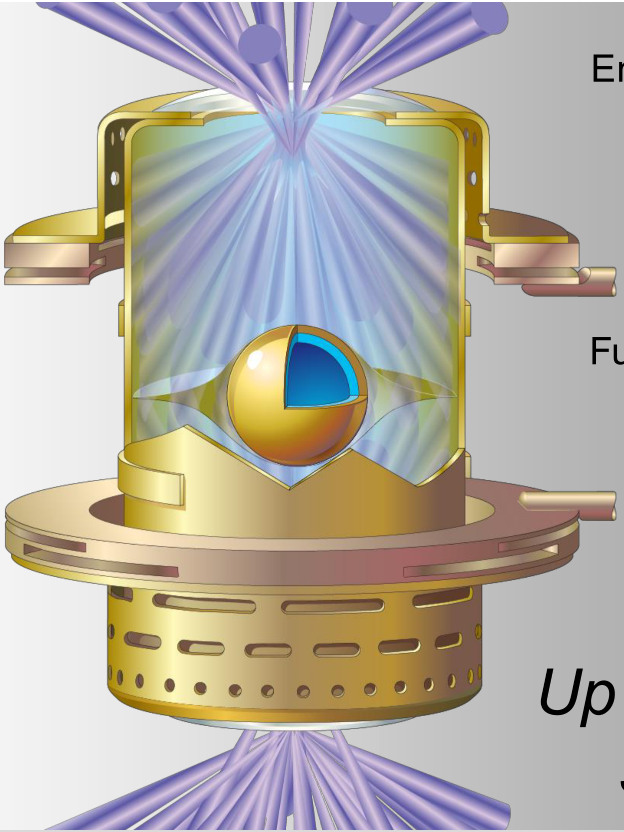
Energy In

Electricity
322 MJ

Laser
2.05 MJ

Capsule
~250 kJ

Fusion Fuel
~20 kJ



Energy Out

Fusion Yield
3.15 MJ

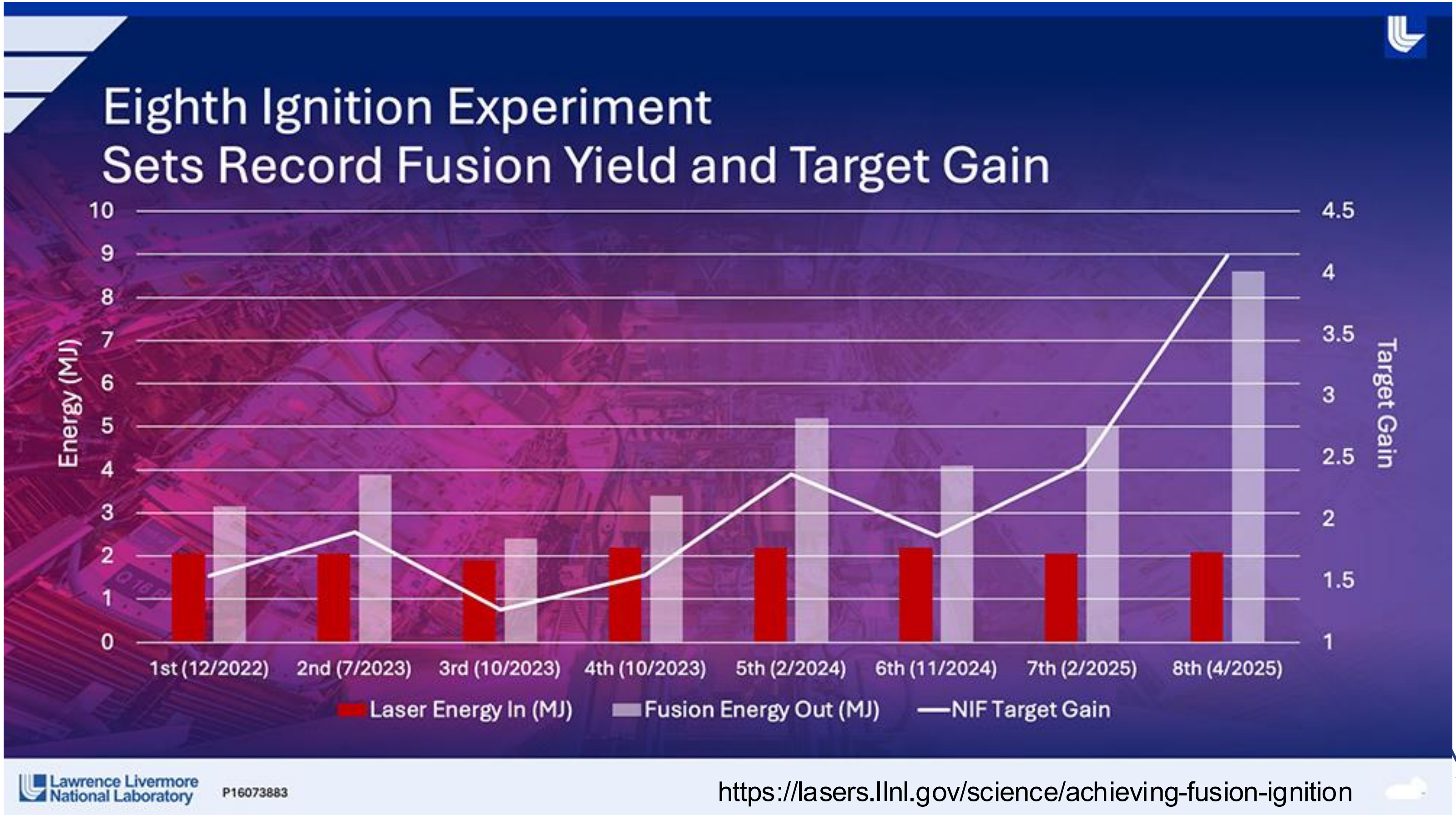
Up to 8 MJ so far

Courtesy:

Lawrence Livermore National Laboratory

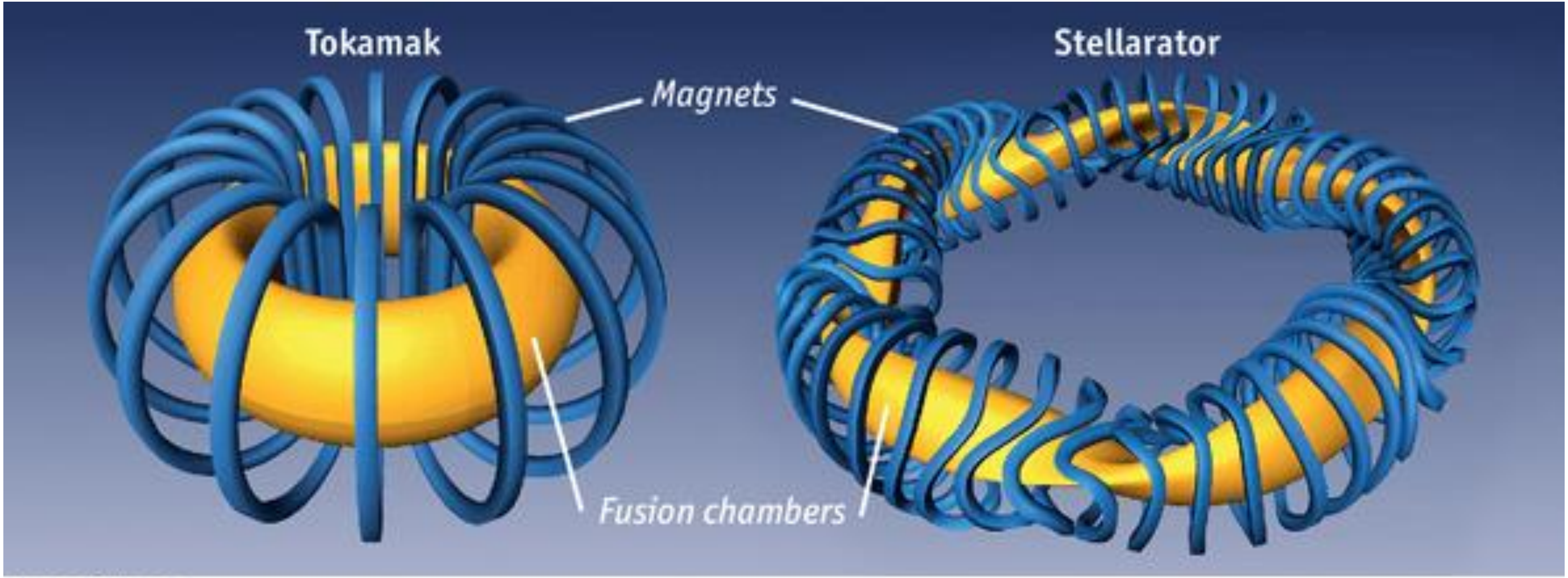
National Nuclear Security Administration

NIF: regularly breaking fusion records !



https://lasers.llnl.gov/science/achieving-fusion-ignition

Magnetic Bottles: Two Types



Economist.com

Additional concepts are being explored ... More later!

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Economist.com

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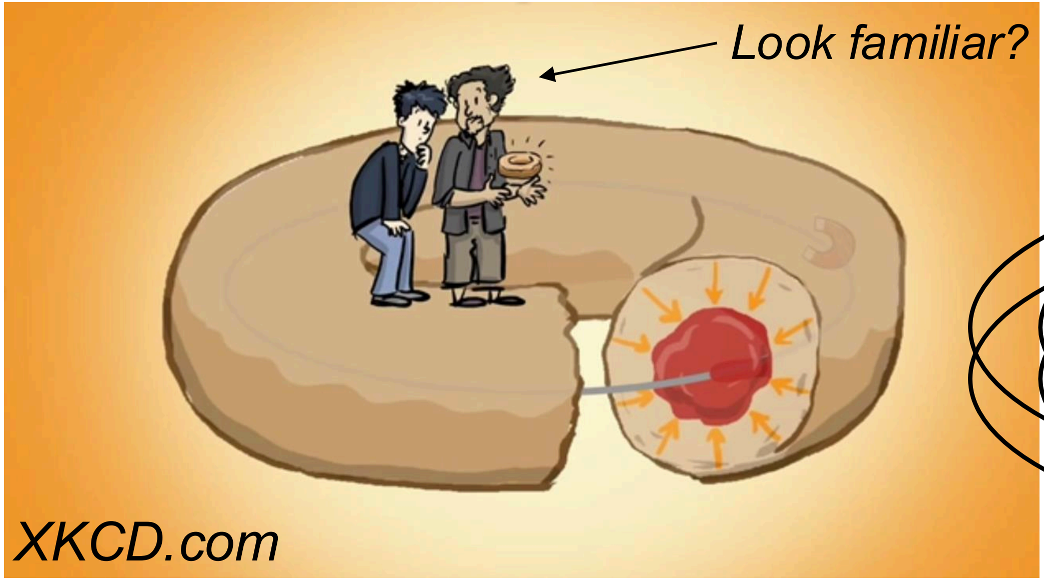
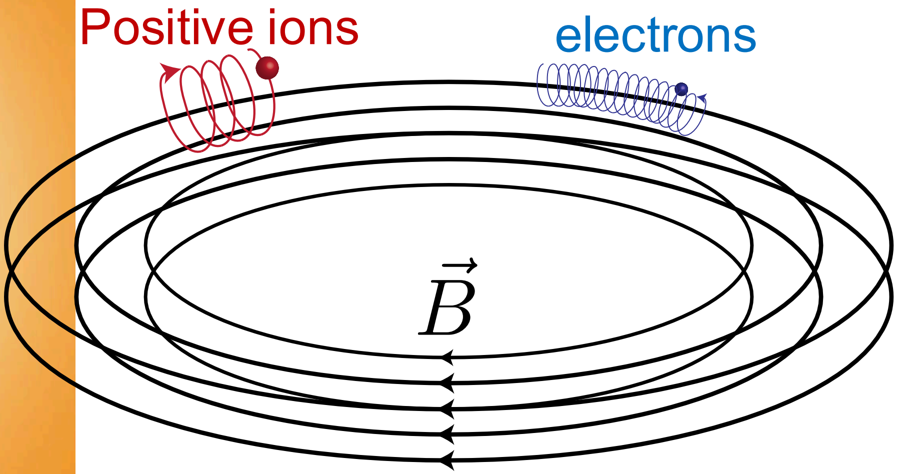
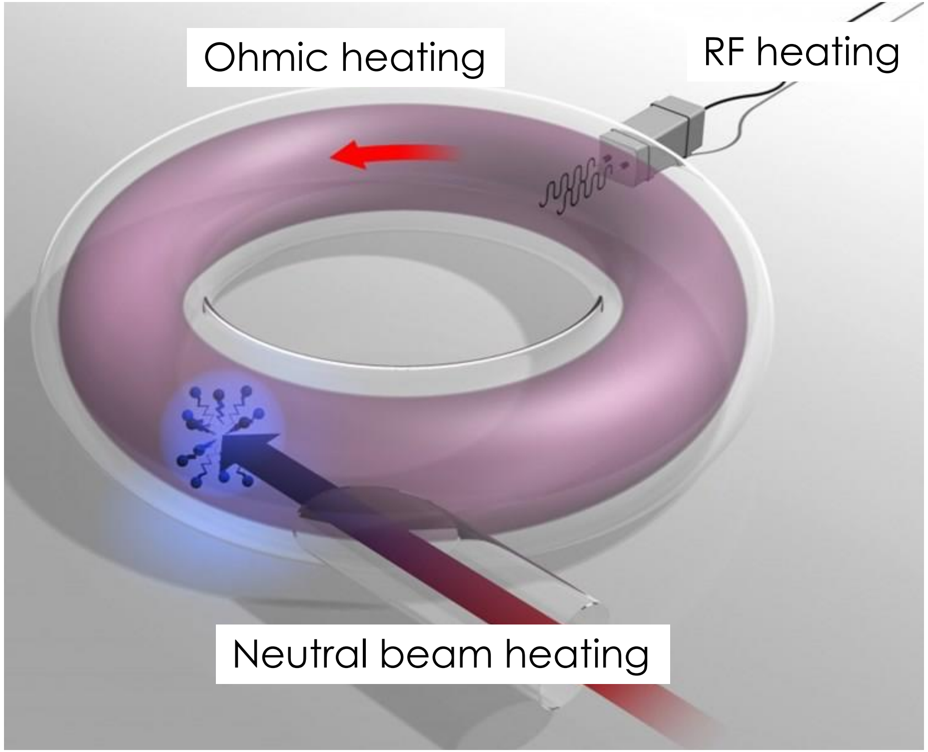
Magnetic Fields Guide the Motion of the Fusion Plasma



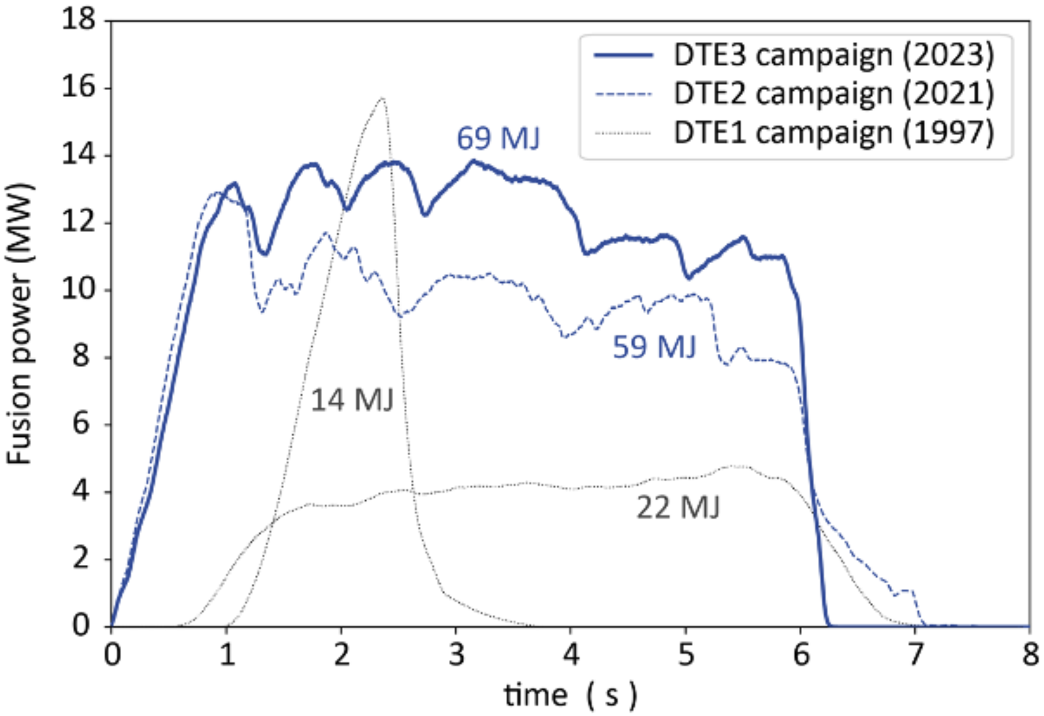


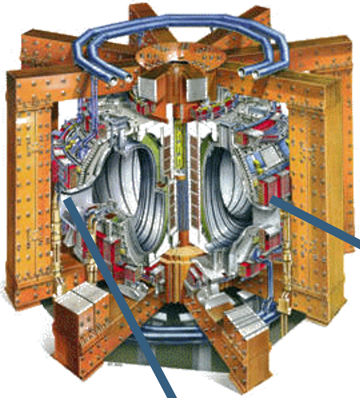
External Heating Necessary for Fusion

- Ohmic heating: like an electric heater !
- Radio-frequency heating: like a microwave oven !
- Neutral beam heating: a particle accelerator !

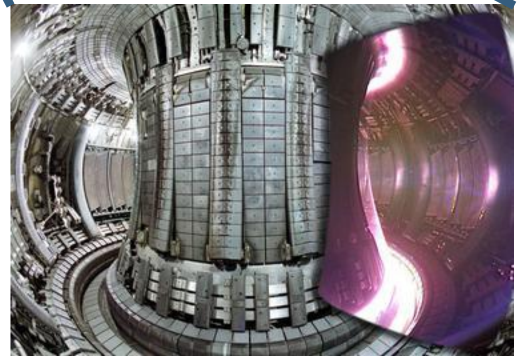


Fusion Energy Record at JET Tokamak





JET
Oxford, UK

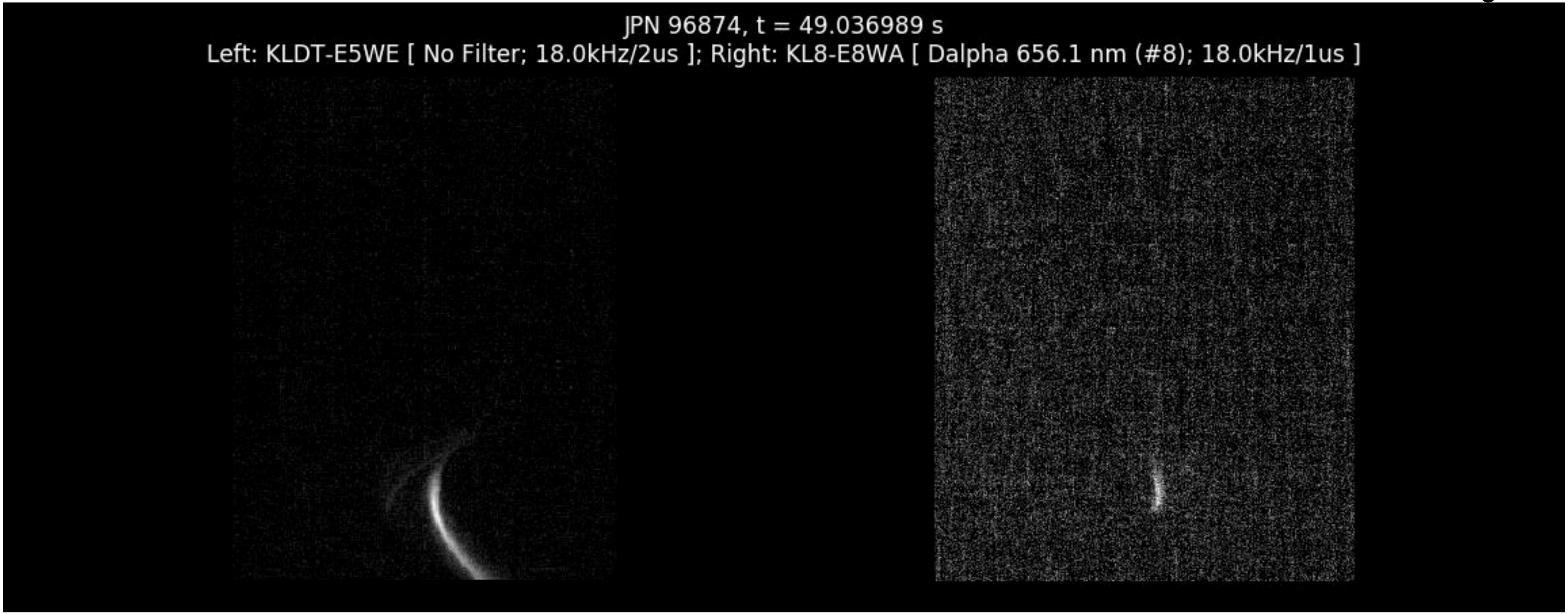


69 MJ ~ 50,000 homes for 1 second

((Q~0.37))

What does it look like inside?

JET Tokamak Device, United Kingdom



Presentation Scope

- Why bother ?
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Ask AI: "fusion energy history"

100 years of fusion. August 24th 1920 The British Association

- Arthur Stanley Eddington -- delivered presidential address:
  "The Internal Constitution of Stars"

- One of the many questions he addressed is:
  "Where does the energy radiated by the stars/sun come from?"

- F. W. Aston had recently measured the masses of elements and shown: $M_{hydrogen}$ = 1.008 and M_{helium}= 4.0 → some was missing !

- Eddington proposed that the sun is transforming hydrogen into helium – thereby liberating "fusion energy". It is. He went on to estimate the sun's lifetime – surprisingly accurately (15 Billion years).

100 years of fusion. August 24th 1920 The British Association

- Arthur Stanley Eddington -- delivered presidential address: *"The Internal Constitution of Stars"*
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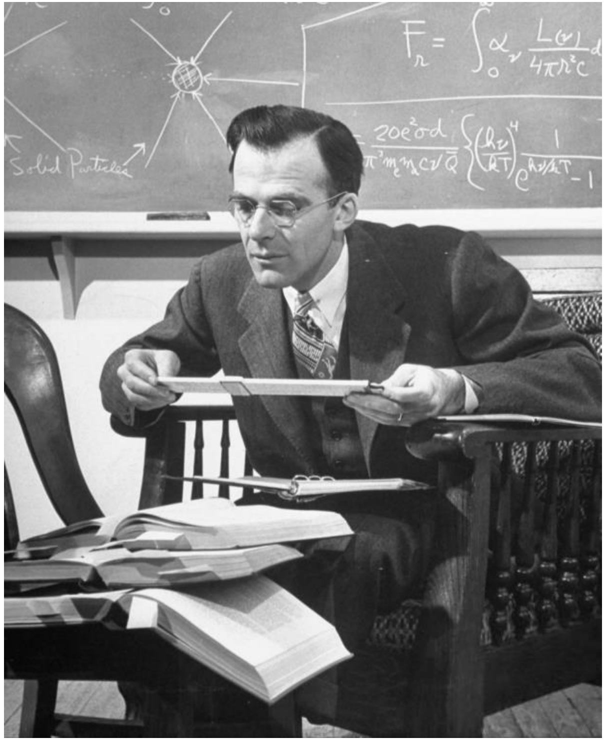
"This reservoir can scarcely be other than the sub-atomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man (!) will one day learn how to release it and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped".
Arthur Stanley Eddington 1920.

- Eddington proposed that the sun is transforming hydrogen into helium – thereby liberating "fusion energy". It is. He went on to estimate the sun's lifetime – surprisingly accurately (15 Billion years).

70 years ago: Argentina & the fusion race

Ronald Richter

Juan Domingo Perón



Lyman Spitzer in 1948

- March 24th 1951: Argentina claims (incorrectly) that scientist Ronald Richter has achieved fusion energy
- July 23rd 1951: Lyman Spitzer proposes (in secret) Project Matterhorn S to develop fusion energy for power production
- Princeton Plasma Physics Laboratory is born – but not named

Early ~1950s Research was Classified

- First US Concept "Stellarator", inspired by the sun
- Project Matterhorn (Princeton) was the hub of activity

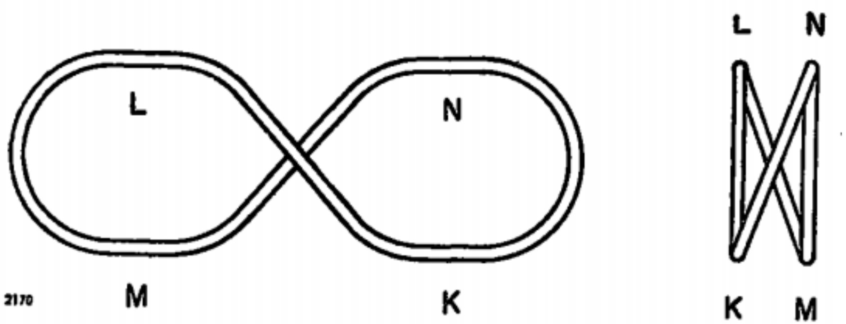


Figure 2. Top and end views of a figure-eight stellarator

Lyman Spitzer (later in life)

COLUMBIA PLASMA PHYSICS

Atoms for Peace: IAEA-FEC 1958

- West & Soviets exchange ideas, 5000 delegates
- “each country's top scientists were set to present the first broad revelation about what they had achieved in fusion”
- **Artsimovich, USSR:** “A most important factor in ensuring success in these investigations is the continuation and further development of the **international cooperation** initiated by our conference. The solution [...] will require a maximum concentration of intellectual effort and the mobilization of very appreciable material facilities and complex apparatus.”
- **Teller, USA:** “It is wonderful that over a large and important area of research we can now all talk and **work together freely**. I hope that this spirit of cooperation will endure, that it will be generally exercised throughout the world in this field and that be extended also to other fields”

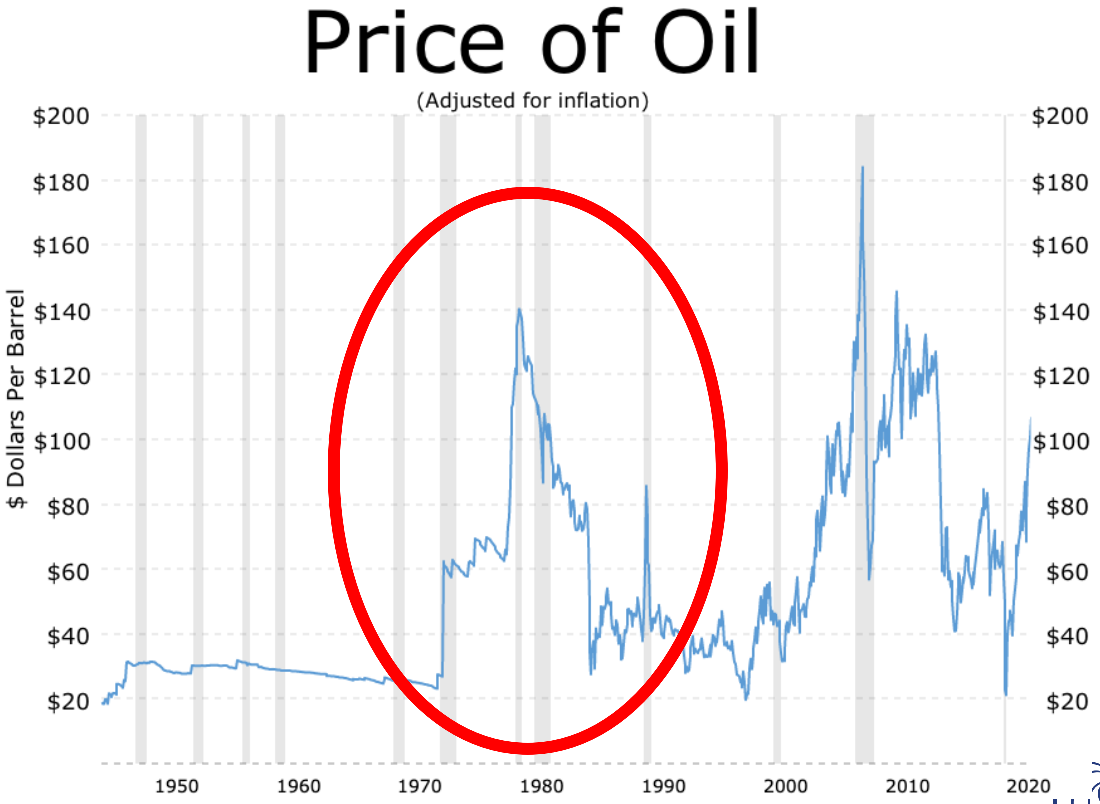
https://www.iter.org/newsline/47/680
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1373588/

1st IAEA-FEC in 1958:
http://www-naweb.iaea.org/napc/physics/2ndgenconf/sets/Home.html

Discovery of 1 keV in USSR (1968) Reorients Fusion Towards Tokamaks

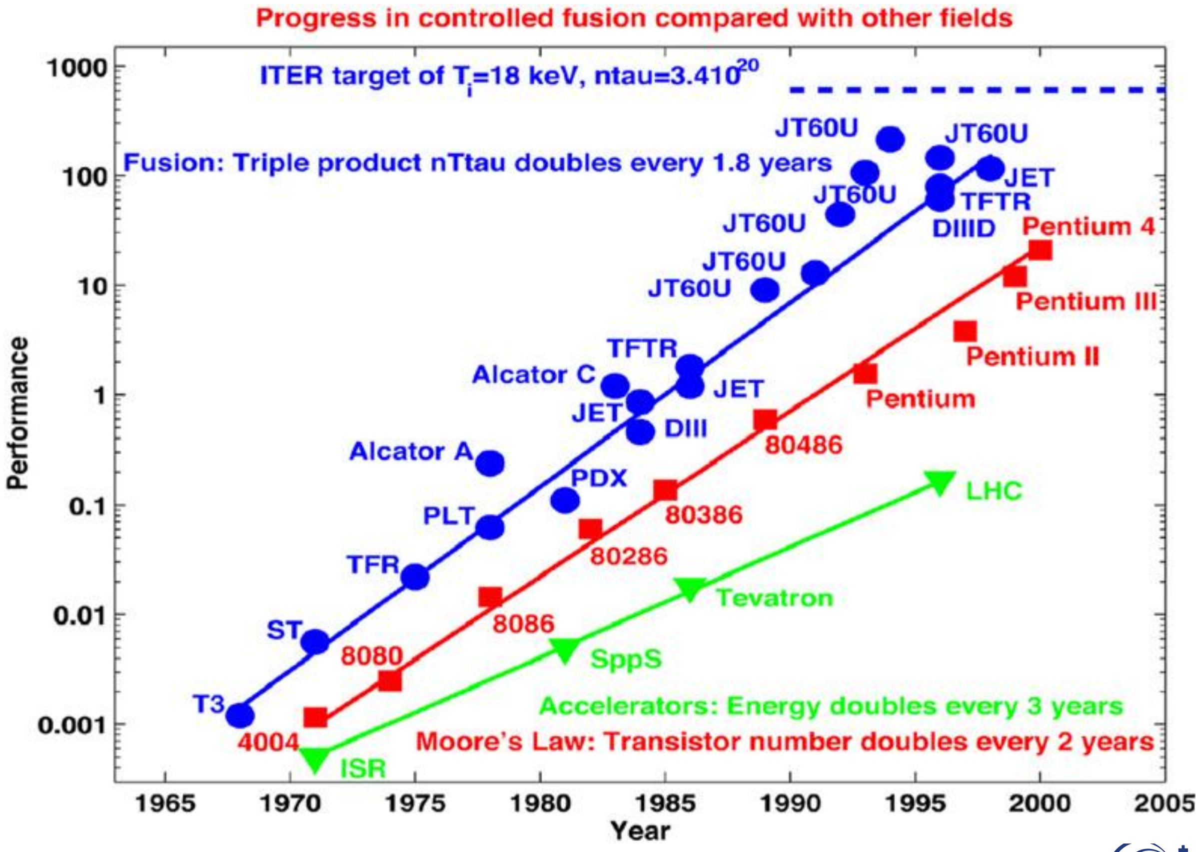
- 1 keV = ~10% of the way to fusion temperatures !!
  - Disbelief at first, verified by visiting UK scientists (via "Thomson Scattering")
- Stellarator at Princeton (Model-C) was converted to a tokamak (to avoid losing funds to rival labs)
  - Performance improved 10x in tokamak mode
- Stellarators the junior partner of tokamaks ever since
  - Wendelstein 7-X in Germany carries the stellarator banner into the future

Societal Pull: Energy Crisis of the 1970s



1970-1980s: Major $$, Major Tokamaks

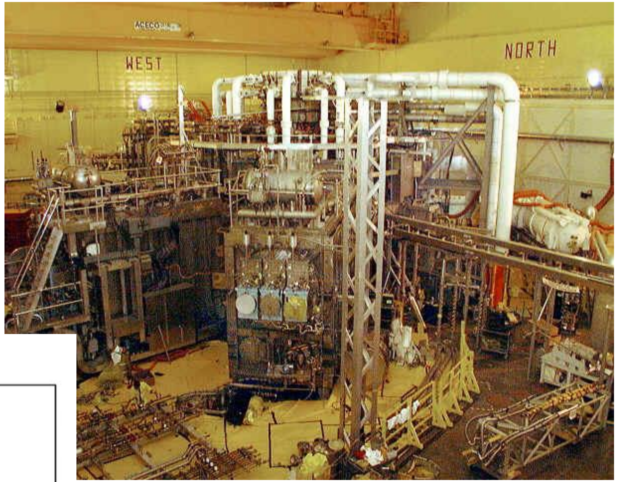
Triple Product

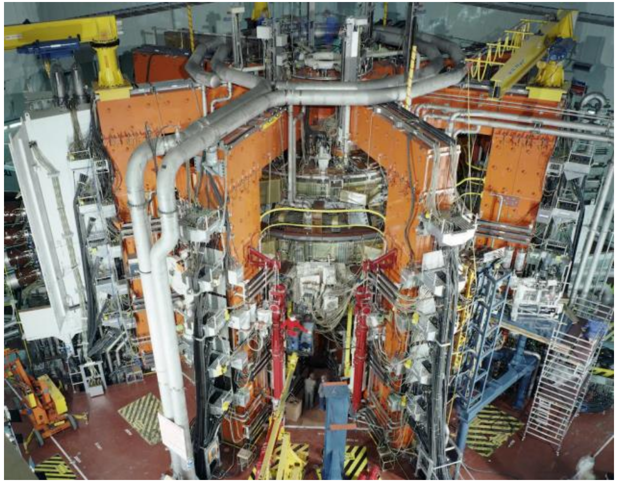


COLUMBIA PLASMA PHYSICS

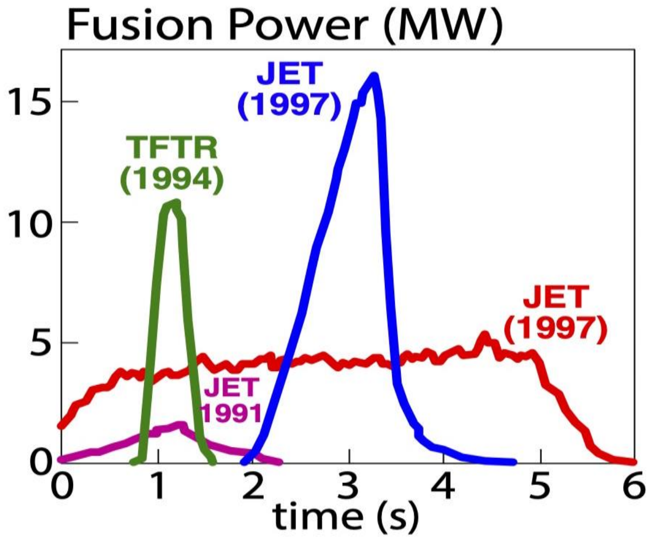
1970-1980s: Major $$, Major Tokamaks

TFTR, United States
First Plasma: 1982
Shutdown: 1997



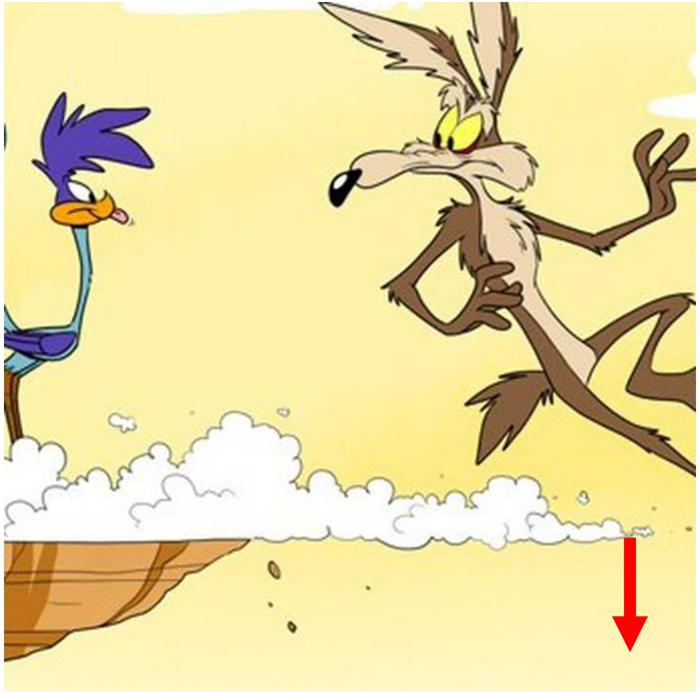


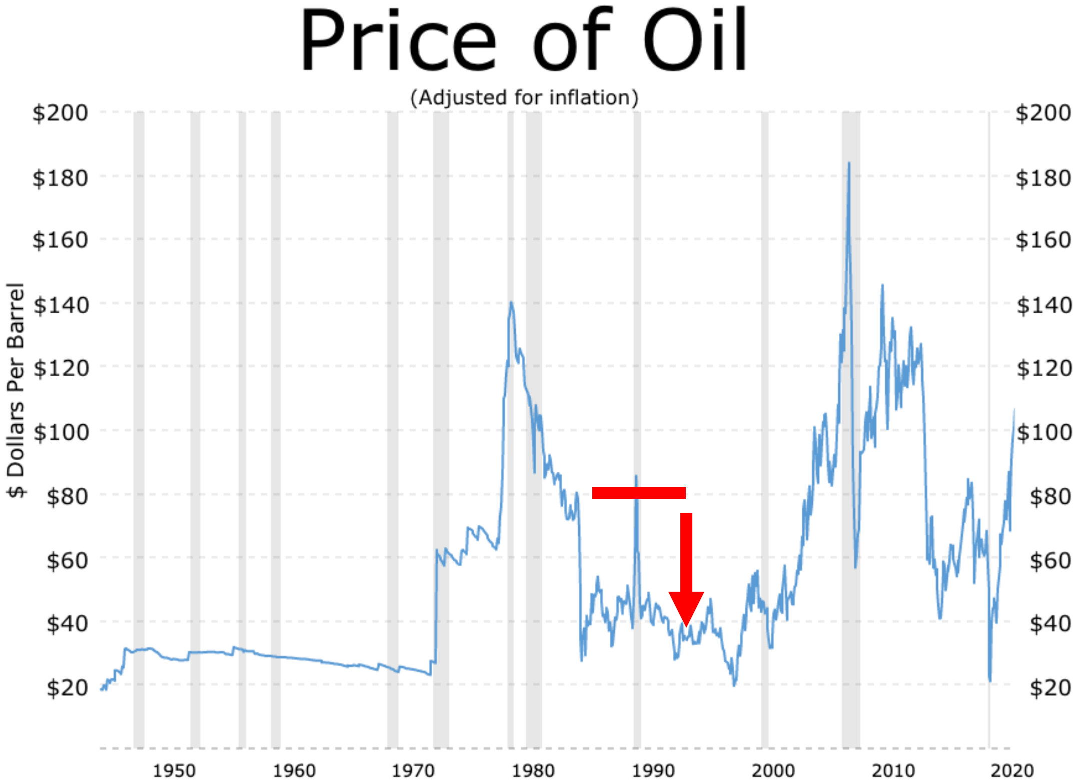
JET, European Union (@UK)
First Plasma: 1983
Shutdown: 2023



Q<1

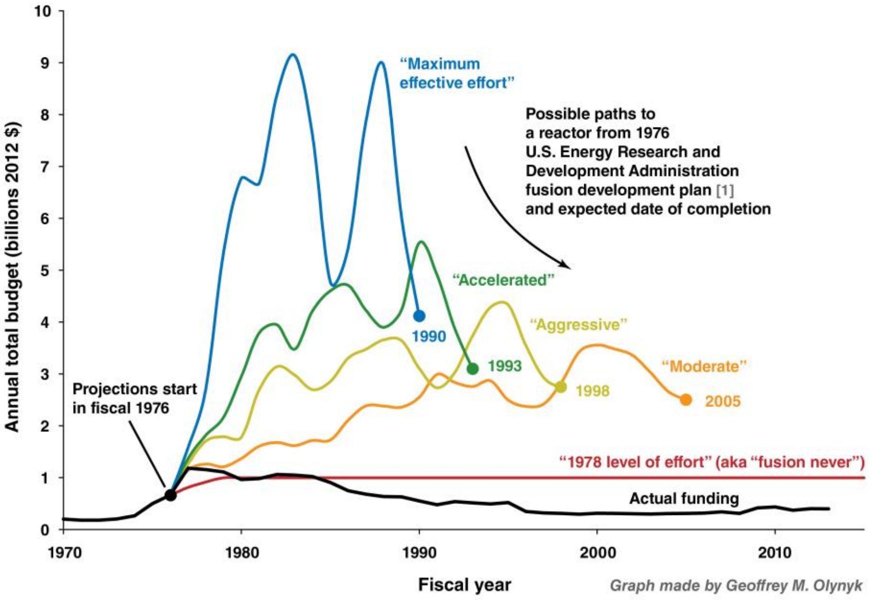
1990s Fusion Budgets: Wile E. Coyote





Fusion Budget 1990s-2010s

- Major doldrums in 1990-2010s (→ *"always 30 years away"*)
- NIF, paid for by weapons program, launched during this time (different societal pull)



[1] U.S. Energy Research and Development Administration, 1976. "Fusion power by magnetic confinement: Program plan" ERDA report ERDA-76/110. Also published as S.O. Dean (1998), *J. Fus. Energy* **17**(4), 263–287, doi:10.1023/A:1021815909065

1990-2010s Survival Mode: “Science Program”

The Fusion Energy Sciences (FES) program has two goals:

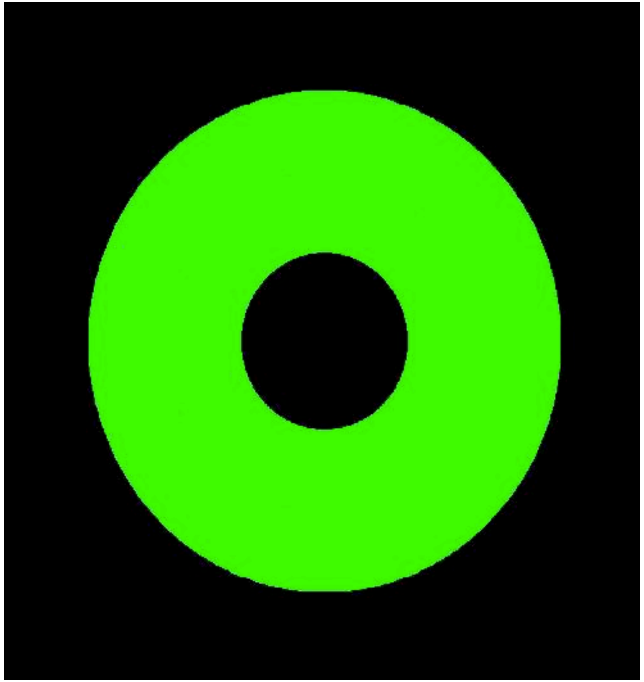
- (1) expand the understanding of matter at very high temperatures and densities, and
- (2) build the knowledge needed to develop a fusion energy source.

((No mention of developing the energy source itself))

https://science.osti.gov/fes

During the Doldrums, Fusion Science Advanced Significantly

- “Plasma Physics” field is vibrant and essential to predicting fusion machine performance
- Sophisticated computation developed to understand and predict the plasma state



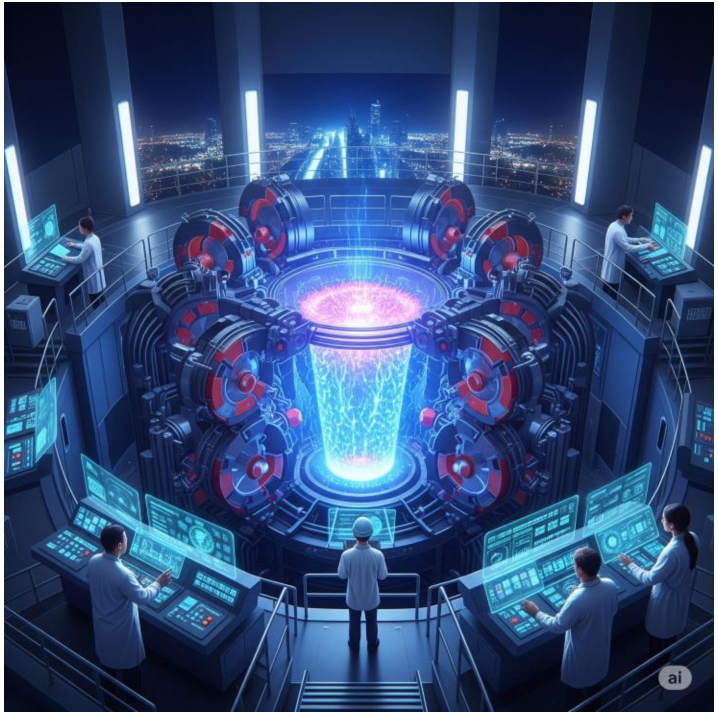
Courtesy: J. Candy & R. Waltz

During the Doldrums, Nations Banded Together to Launch ITER

- Fusion/Tokamaks identified as area of cooperation between US / USSR
- US participation was hit-or-miss
- Other nations (EU) joined along the way

Presentation Scope

- Why bother ?
- What conditions are required ?
- What are the approaches ?
- Where have we been ?
- Where are we going ?



Ask AI: "future of fusion energy"

2020s: Mood has Changed for Fusion

- Societal pull is back: Extreme weather events / climate change
- New technologies offer faster less costly development path
- Scientific basis illustrates fusion conditions can be met
  - Example: calculations of plasma heat transport from turbulence (last slide)
- Net energy gain w/ laser fusion 2022, magnet fusion coming soon

Clear change in perception and support for fusion

2021: Magnet Technology Leaps Forward

Fusion startup builds 10-foot-high, 20-tesla superconducting magnet

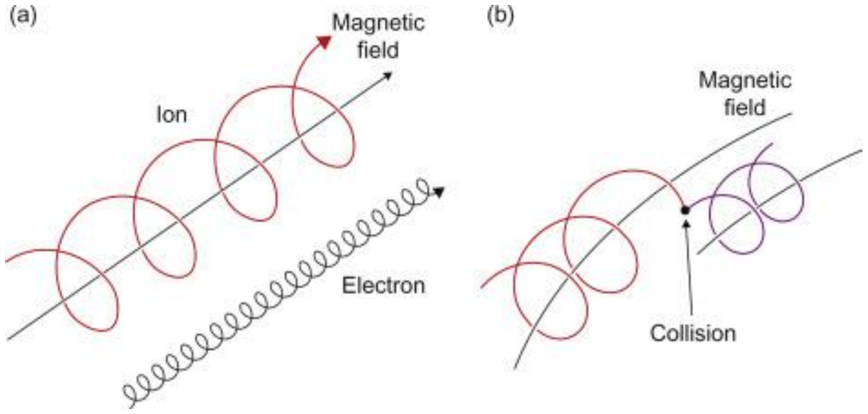
Calculations indicate the magnet should allow fusion to break even, energy-wise.

JOHN TIMMER - 9/8/2021, 4:43 PM

Stronger magnets enable size & cost reduction

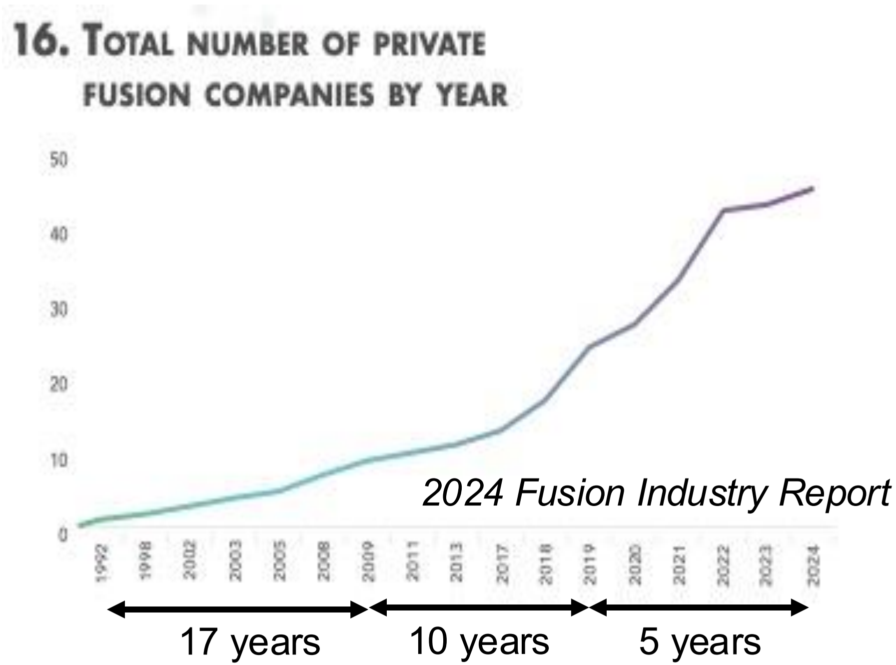
Why does Magnetic Field Reduce Size?

- Particles follow helical paths in magnetic fields
- "Orbit Width" decreases with magnetic field strength
- Number of orbits that fit inside fusion device is the real "size" that matters
- 2x radius drop = 8x volume drop (crudely, cost scales like volume)



Today:
Private Sector Explodes on the Scene

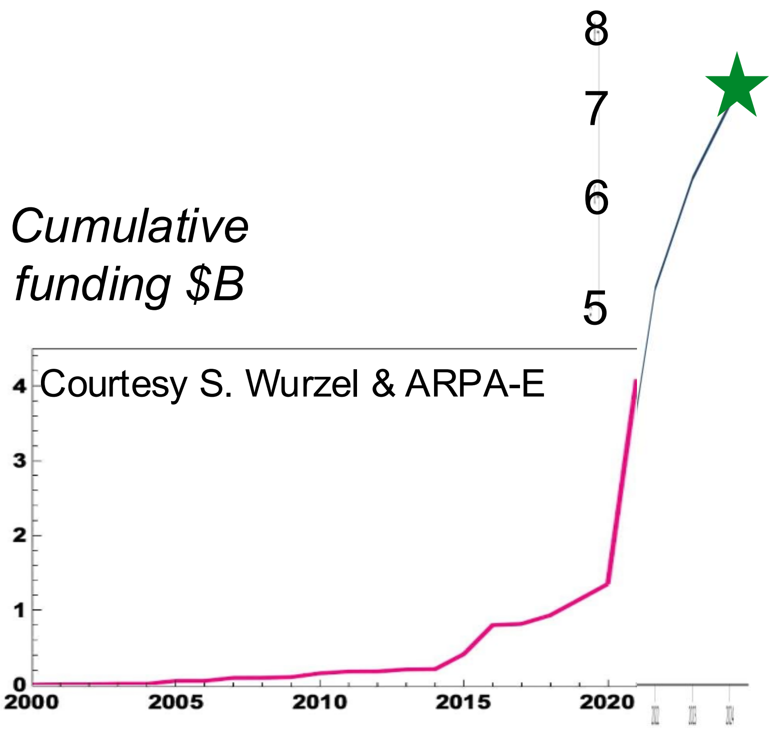
- Explosion of companies
- Many different technical approaches
- Many shapes of magnetic bottle, many lasers, many hybrid techniques



Columbia Plasma Physics

Record Venture Capital Investment

- Around ~ $7B private funding total into fusion companies
- Investment continuing despite higher interest rates, inflation
- Future $$ depends on level of <u>technical success</u>
- Timeline depends on funding!



COLUMBIA PLASMA PHYSICS

The Fusion Industry: SpaceX Wannabes

These all want to be like:

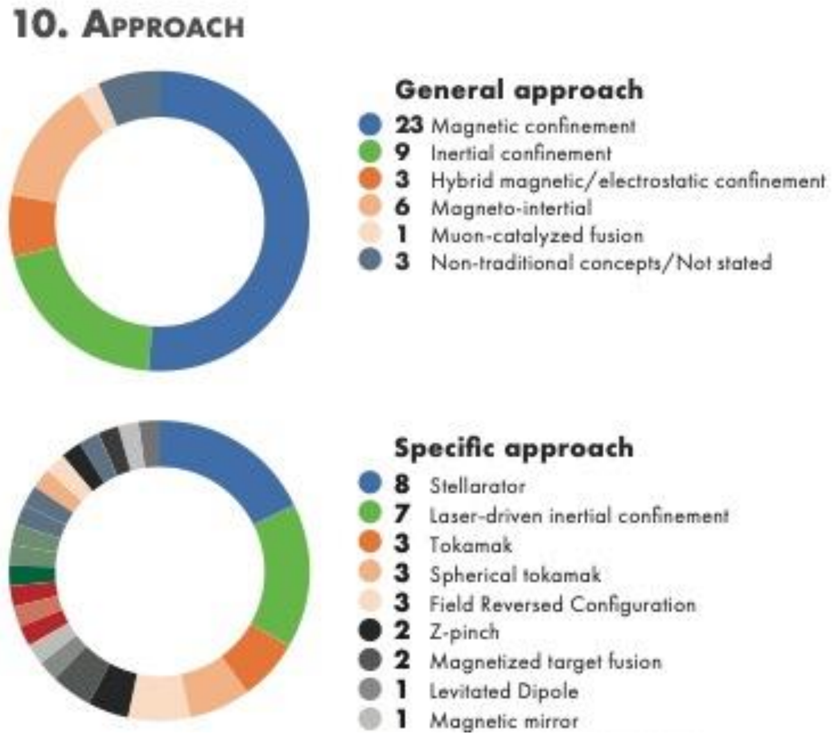
SPACEX

(for fusion)

https://www.fusionindustryassociation.org/

What is Fusion Industry Pursuing?

- Venture capital sponsored a wide spectrum of approaches (lower barrier to entry)
- Best funded is “Commonwealth Fusion Systems” in MA (Tokamak)
- Most popular concept is the stellarators (many smaller firms)
- Laser/Inertial has received significant investment also



(...many more @ 1)

2024 Fusion Industry Report

2023: US Dept Energy Launches “Milestone” Program

- Cost-sharing program between DOE and fusion industry
- When certain milestones are met, DOE funding unlocked
- Modeled on “NASA COTS” (SpaceX’s seed funding from NASA)

Company	Project
Commonwealth Fusion Systems	Commercial fusion power on a decadal timescale with the compact, high-field ARC power plant.
Focused Energy Inc.	Inertial Fusion Energy with High-Gain Proton Fast Ignition.
Princeton Stellarators Inc.	Stellarator Fusion Pilot Plant Enabled by Array of Planar Shaping Coils.
Realta Fusion Inc.	The High-Field Axisymmetric Mirror on a Faster Path to Fusion
Tokamak Energy Inc.	ST-E1 Preliminary Design Review for a Fusion Pilot Plant.
Type One Energy Group	The High-Field Stellarator Path to Commercial Fusion Energy.
Xcimer Energy Inc.	IFE Pilot Plant with a Low-Cost, High-Energy Excimer Driver and the HYLIFE Concept.
Zap Energy Inc.	Development of a Fusion Pilot Plant Design Based on a Sheared-Flow-Stabilized Z Pinch.

https://www.powermag.com/fusion-energy-projects-get-boost-from-doe-funding/

Example Company Roadmap to Fusion

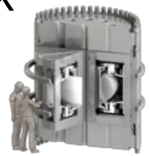
Research Phase
(~ $10s-100 million)

Energy Gain
Demonstration Device
(~ $ billion)

First Power to the grid
~ $5B

R&D

Physics
Design
Work



COMPLETED

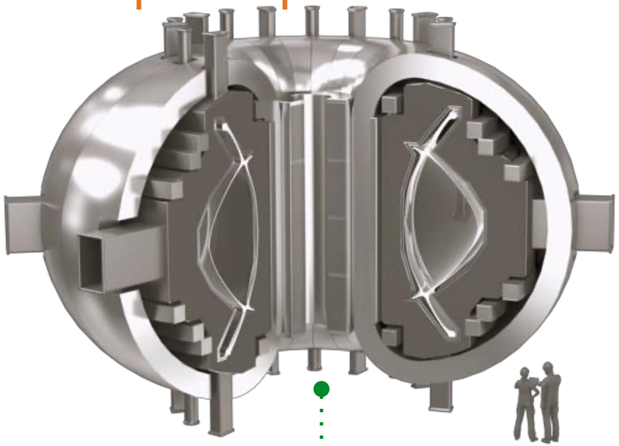
Technology
Demonstrator

COMPLETED

Commercial
demo

UNDER
CONSTRUCTION

Commercial
powerplant



EARLY
2030s

Courtesy Commonwealth Fusion Systems

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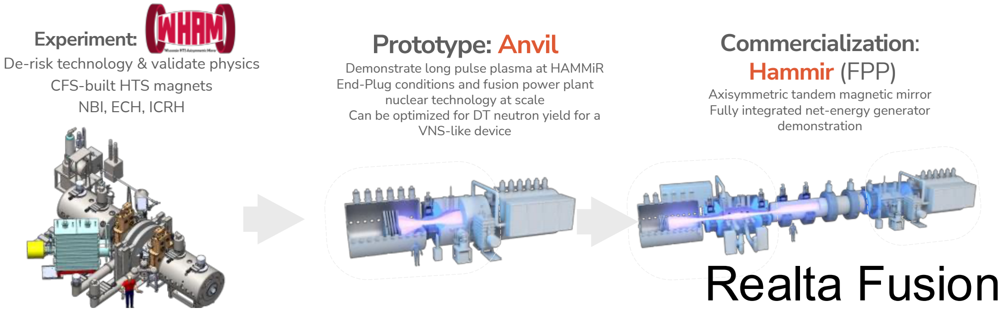
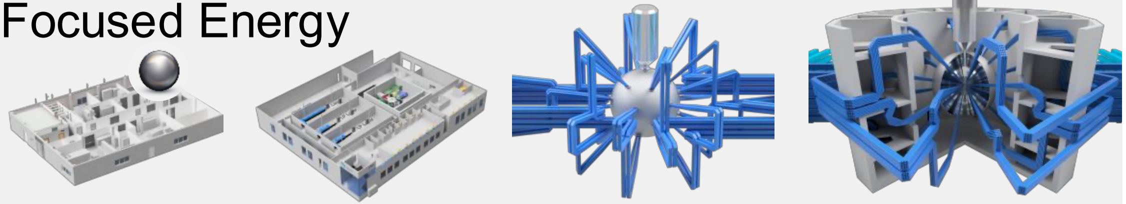
More Company Roadmaps

Thea Energy



Realta Fusion

Focused Energy



Target Laboratory
Precision-engineered targets
Developing technology for automated manufacturing (TRL 4)

Laser Facility
Laser development and testing
Experimental validation
Scientific de-risking (TRL 4)

Integrated Test Facility
Integrated systems testing and design optimization
Proving design/engineering viability of full-scale fusion plant (TRL 6)

Fusion Pilot Plant
Q_{eng}>1 demonstration facility, at 10 Hz operation
Full-scale proof of technical and commercial viability (TRL 8)

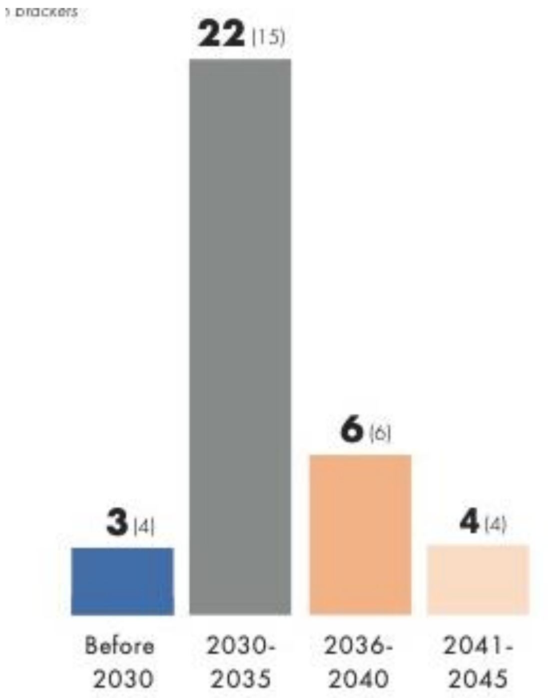
<u>When is fusion on the grid?</u>

- When these steps are completed
- Each approach takes many $B
  - Failure is possible!
- Supporting (public-sector) R&D needed for all paths (several ~$B)

Industry Timelines: Aggressive

- My view: industry's vision requires significant additional investment
  - Into the companies directly to execute roadmap
  - Into the public sector for supporting R&D
- Right now, only a few companies are funded enough for 2030s to be credible, *money ←→ time*
  - Breakeven announcements in demo devices should liberate big investments for first plants
  - Plant step will take additional time (5+ years)
- Keep track of $$, breakeven announcements to see if each stays on track or falls behind

"When do you anticipate your company will deliver power to the grid"



2024 Fusion Industry Report

ITER Project in 2025

- Most components fabricated and delivered
- Issues in assembly have caused significant delay
- Progress in ITER contributed to current positive fusion climate

ITER Project in 2025

- Most components fabricated and delivered
- Issues in assembly have caused significant delay
- Progress in ITER contributed to current positive fusion climate

Nuclear Regulatory Commission (NRC) has recognized Fusion's unique status

- NRC will treat fusion as an "accelerator", NOT a fission reactor "utilization facility"
- Recognizes the inherently lower risk profile of fusion
- Significant positive benefit to economics of fusion
- Fewer (no?) "intervenor" issues

CLEAN ENERGY

Nuclear fusion will not be regulated the same way as nuclear fission — a big win for the fusion industry

PUBLISHED THU, APR 20 2023·3:43 PM EDT | UPDATED THU, APR 20 2023·5:10 PM EDT

Catherine Clifford
@IN/CATCLIFFORD/
@CATCLIFFORD

SHARE

April 2023

https://www.nrc.gov/reactors/new-reactors/advanced/policy-development/fusion-energy.html

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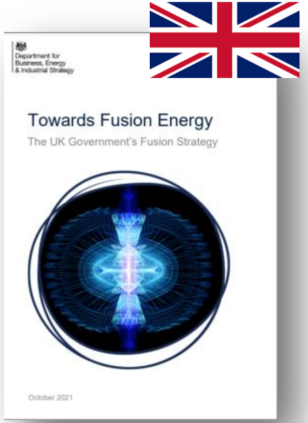
International Race to Fusion

$790M/yr

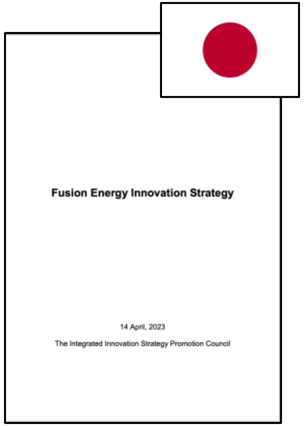
(Office of Science FES)



$250M/yr

$520M/yr

$1500M/yr (est., MFE)



$237M/yr

South Korea: ~$87M/10 yrs starting 2026

COLUMBIA PLASMA PHYSICS

COLUMBIA
PLASMA PHYSICS

Fusion
& Budget Austerity

- New administration is very serious about reducing spending
- Science is targeted for reductions in FY26 White House budget request
- Fusion is favored by new admin, fingers crossed US' fusion dreams won't be put on hold

Discretionary funding change, 2025-26

	BILLIONS	PERCENTAGE CHANGE
State and International Programs	−$49.1	−84%
National Science Foundation	−$4.9	−56%
Environmental Protection Agency	−$4.9	−54%
Housing and Urban Development	−$33.5	−44%
Labor	−$4.7	−35%
Small Business Administration	−$0.3	−33%
Interior	−$5.1	−30%
Health and Human Services	−$33.2	−26%
NASA	−$6.0	−24%
Treasury	−$2.7	−19%
Agriculture	−$5.0	−18%
Commerce	−$1.7	−17%
Education	−$12.0	−15%
Justice	−$2.8	-8%
Social Security Administration	No change	
Energy	+$1.3	+3%
Veterans Affairs	+$5.4	+4%
Transportation	+$1.5	+6%
Defense	+$113.3	+13%
Homeland Security	+$42.3	+65%

Note: Amounts are base funding (nonemergency) and include changes the administration is anticipating from the reconciliation process. They do not include offsets or the V.A. Toxic Exposures Fund. • Source: Analysis of budget data by Bobby Kogan, Center for American Progress • By Alicia Parlapiano

Department of Energy Office of Science	-1,148 *-17%*	The Budget reduces funding for climate change and Green New Scam research. The Budget maintains U.S. competitiveness in priority areas such as high-performance computing, artificial intelligence, quantum information science, fusion, and critical minerals.

"Skinny budget FY26"

PLASMA PHYSICS

Presentation Scope

- Why bother ? Firm, low-carbon, dispatchable
- What conditions are required ? Tunnel past the coulomb barrier = Triple product > 8 atm-s @ 10 keV
- What are the approaches ? Tokamak, laser, stellarator, alternates for both magnetic and inertial
- Where have we been ? We're in the second great moment for fusion – past glory gave us JET and TFTR
- Where are we going ? Industry leads the charge to a power plant
  Turbulent times ahead!

Columbia's Plasma / Fusion Program

COLUMBIA
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- 5 core faculty
- ~12 scientist/post-docs
- ~30 grad students
- ~45 undergrads
  +Summer REU Program
- Largest lab on campus (ft^2)

Columbia's Plasma / Fusion Program

- On-campus plasma and fusion tech. experiments

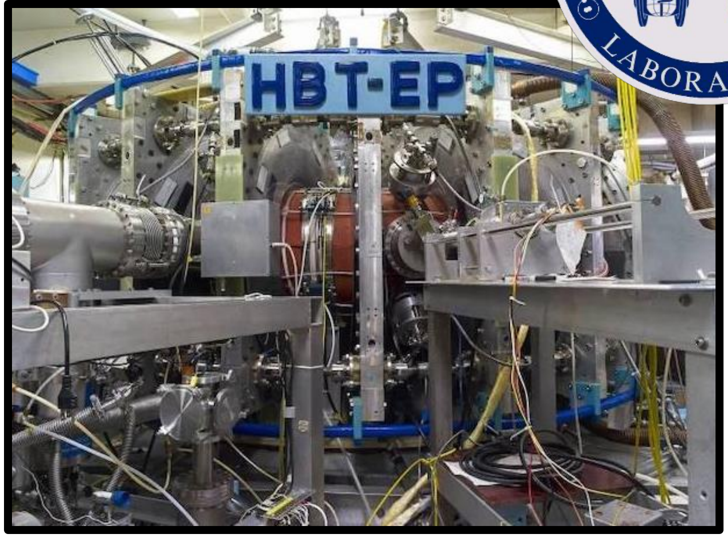
Tokamak

~ 1.5 meter

Stellarator

+ *Fusion Technology*

Tokamak



~ 2 meter

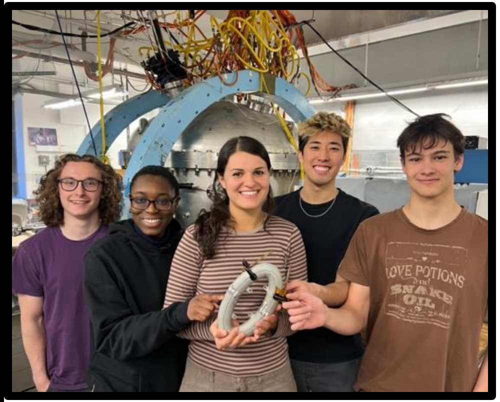
Columbia's Plasma / Fusion Program

- On-campus plasma and fusion tech. experiments

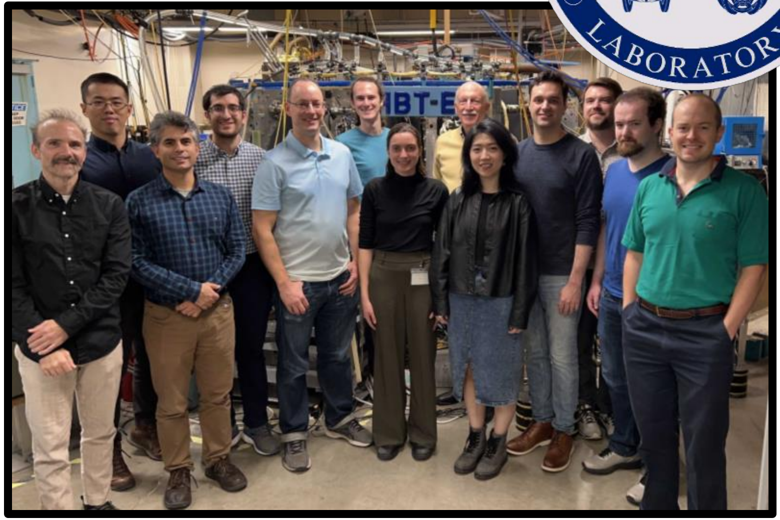
Tokamak

~ 1.5 meter

Stellarator



Tokamak



~ 2 meter

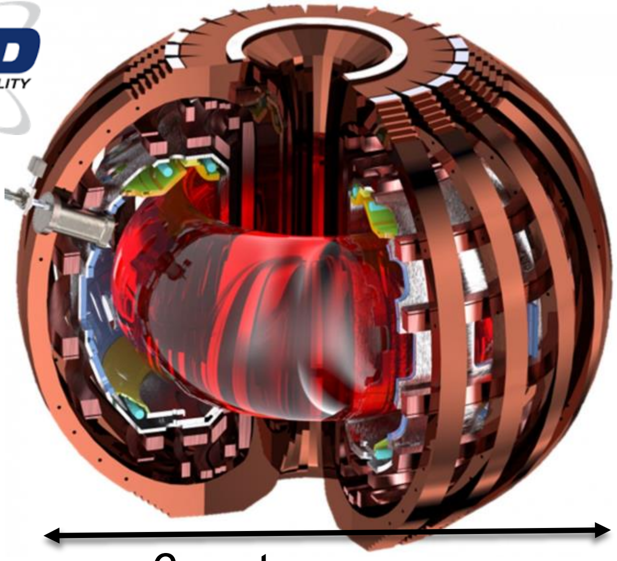
+ *Fusion Technology*

Columbia's Plasma / Fusion Program

- On-campus plasma and fusion technology experiments

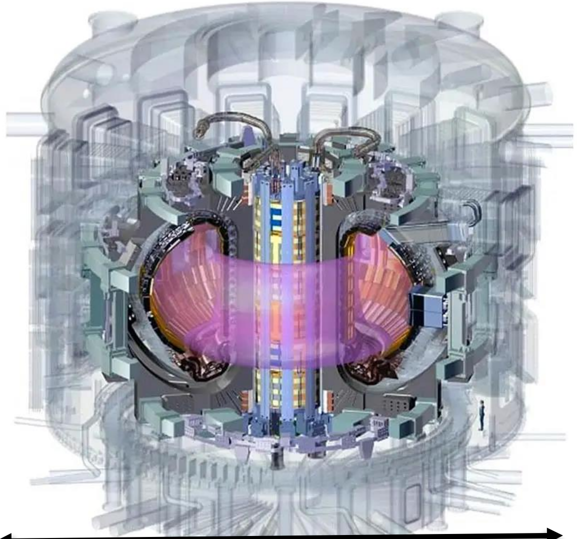
- Fundamental research in public-sector large tokamaks

DIII-D
NATIONAL FUSION FACILITY



~ 6 meter

iter
china eu india japan korea russia usa



~ 28 meter

Columbia's Plasma / Fusion Program

- On-campus plasma and fusion technology experiments
- Fundamental research in public-sector large tokamaks
- Strong engagement with private fusion sector

NEXT STEP FUSION

Tokamak Energy

TYPE ONE ENERGY

Commonwealth Fusion Systems

THEA ENERGY

OPENSTAR TECHNOLOGIES LTD

Mostly industrially sponsored research with some public cost-sharing schemes

Want to get involved?

- Columbia : https://fusion.columbia.edu/
- US Program: https://usfusionenergy.org
- Fusion Industry: https://www.fusionindustryassociation.org
- Universities: www.universityfusionassociation.org