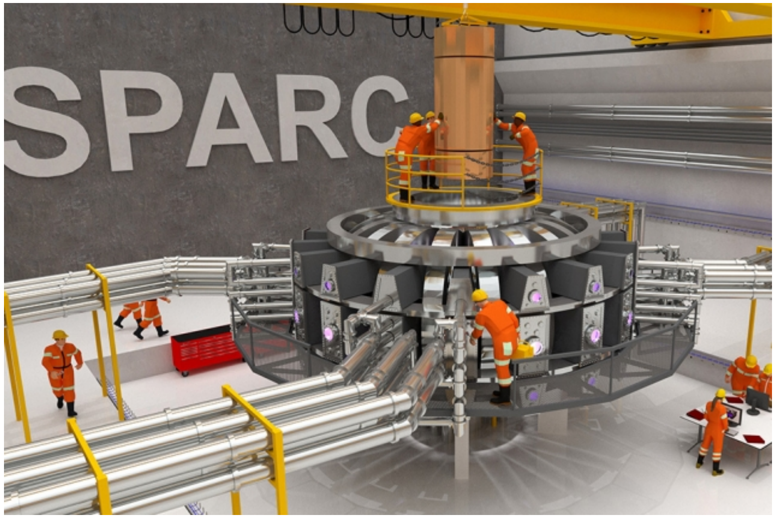
Frontiers in Commercializing Fusion Development:
The New Landscape of Companies Investing in Fusion Worldwide

Dr. Octopus confronts a plasma instability in the film Spider-Man 2 (2004)



Artist's rendering of the SPARC experiment, Commonwealth Fusion Systems

Talk Scope

- Introduction to thermonuclear fusion
- Why now? Models, hardware, economy, and new government programs
- Overview of existing fusion research efforts, including a **dozen** private companies
- Cutting through the hype: what to expect in the future

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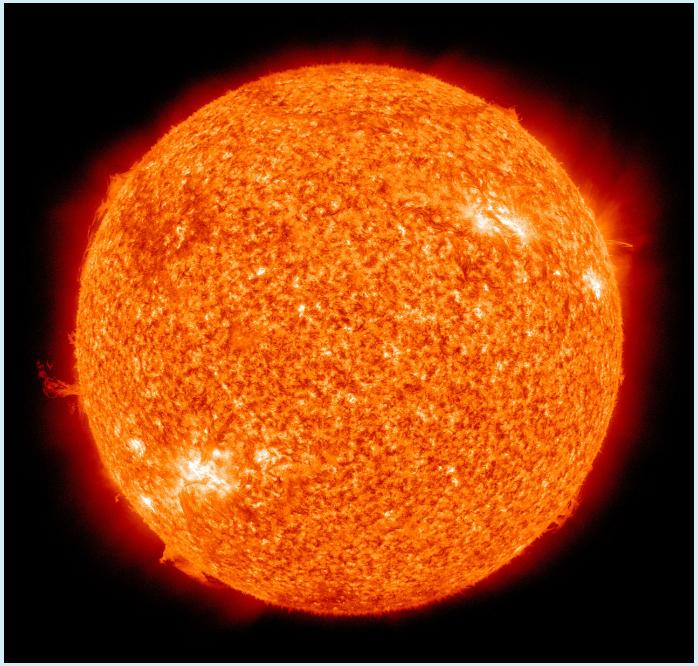
Introduction to Thermonuclear Fusion

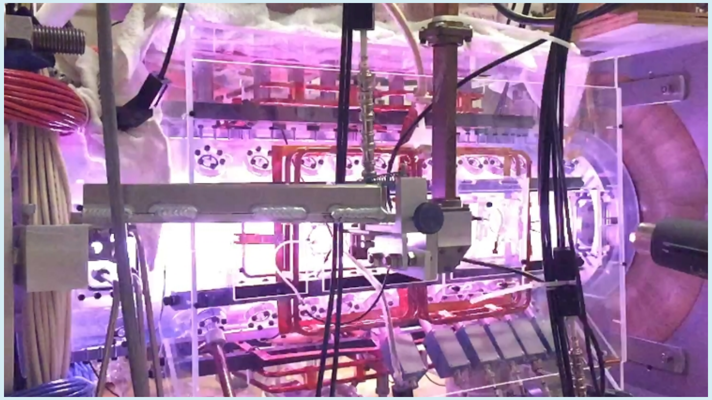
- Fusion is the process of combining small atomic nuclei (hydrogen) into large atomic nuclei (helium). This releases energy.
- Fusion is the opposite of fission, in which large atomic nuclei (uranium) split into small atomic nuclei. This releases energy.
- **Fusion occurs naturally in the core of stars**. Our very own sun is powered by fusion.
- The sun has a big advantage: 250 billion atmospheres of pressure. We may never match this parameter.
- Our advantages: We can make material hotter (200 million K vs 10 million K) and we can use a more reactive (x10^{20}!) fuel (heavy hydrogen isotopes)



The sun is powered by natural nuclear fusion. Credit: NASA/SDO

Why does fusion require ***plasma***?

- At fusion temperatures (100 million degrees), no matter exists in solid, liquid, or gas phases. All matter exists as **plasma**, which is like an electrically conductive gas.
- This is good for us, because plasma can be **confined with large magnets** to keep the heat from leaking out and cooling the plasma
- The trick of artificial fusion, what has made it so elusive, is keeping the plasma **hot**. Heat that leaks out must be replaced via heating systems. This has driven reactor designs toward **larger** structures, **stronger** magnets, **higher** heating power.



This plasma is confined magnetically in the PFRC-2 experiment at PPPL

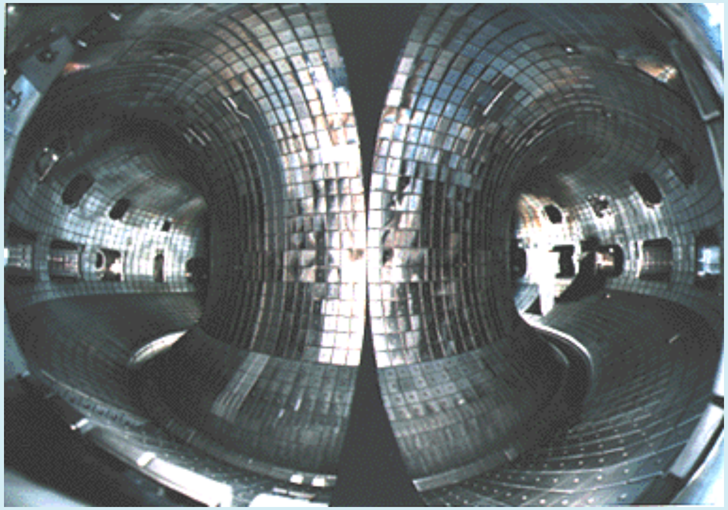
The Promise of Fusion

Power that is:

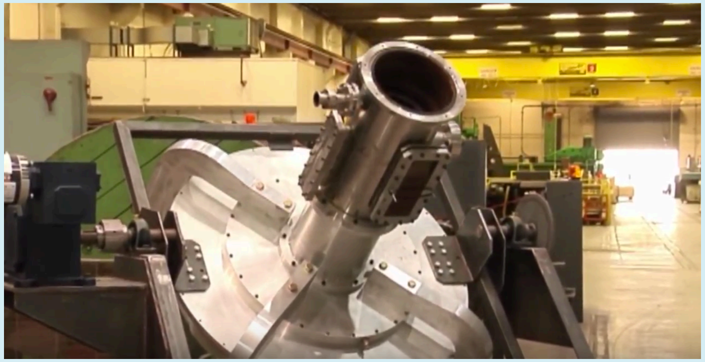
- Abundant
  - The fuels are made from **abundant elements**, and only small quantities are needed (**100 lb could power New York for a year**)
  - Required resource extraction is minimal
- Safe
  - Fusion reactors **can not melt down**
  - Some fusion reactor designs produce radioactive waste, but it is small amounts and short-lived
- Clean
  - Fusion reactors do not release carbon dioxide or any pollutant
  - No contribution to **climate change**
  - No contribution to ecological contamination

The State of the Art

- The largest fusion reactors in the world are experiments
- Doughnut-shaped magnets called Tokamaks
- Tokamaks ***have*** produced MW of ***fusion power***
  - Joint European Torus in UK produces 16 MW of fusion in 1997
  - Required 27 MW of heating power
- Tokamaks ***have*** produced the conditions predicted to be required for ***breakeven***
  - JT-60 in Japan produces temperature and density necessary for Q=1.25 in 1998
- Some commercial fusion reactors (non-tokamak) are in fact available
  - A Dense Plasma Focus is a device for producing fusion neutrons on demand
  - Applications in imaging and materials
  - Consumes much more energy than is released, but energy is not the only economic niche



JT-60 (https://alltheworldstokamaks.wordpress.com)



A dense plasma focus at NNSS

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After Breakeven… Net Tritium?

If breakeven isn't the problem, what is?

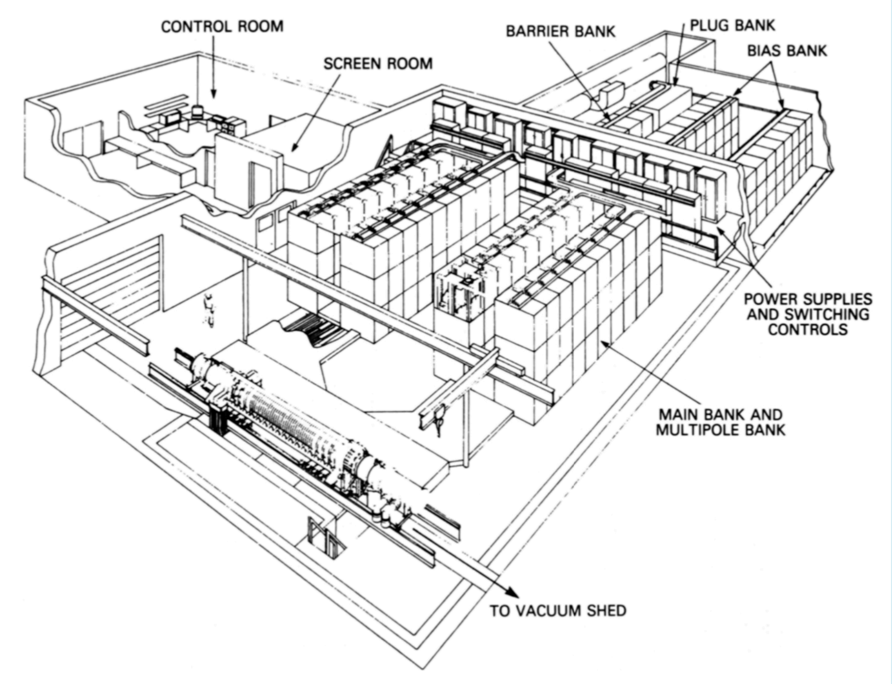
- **Control**: Tokamaks suffer disruptions, which are a sudden loss of plasma. This can damage the tokamak.
- **Divertor**: Where the plasma touches a solid surface, the heat flux is 1000x higher than the leading edge of the Space Shuttle
- **Neutron damage**: When D+T fuse, a 14 MeV neutron is produced. This is much higher energy than the neutrons produced through fission
- **Tritium breeding**: The isotope of tritium must be bred from lithium under neutron flux. This has not been demonstrated!
- **Capital cost**: ITER is currently budgeted for ~$40B

An area of melted tungsten after a disruption in the T-10 tokamak
https://doi.org/10.1016/j.nme.2016.11.029

Theme: Revisiting Old Ideas

Many of these companies are reviving **old ideas** originally studied by governments:

- <u>FRC:</u> Studied by the US DOE since the 1970s, peaking in the 1990s with the $14M LSX experiment
- <u>Z-pinch:</u> The earliest fusion configuration, developed in the USA, UK, and USSR independently in the 1950s
- <u>Spindle cusp:</u> Studied in the 1950s
- <u>Spheromak:</u> Discovered theoretically in 1979, peaking in the 1980s with the CTX experiment
- <u>Compressed compact toroid:</u> Various methods studied by US DOE, particularly the liquid liner Linus program in the 1970s



Drawing of the LSX experiment at Los Alamos in 1993.
Hoffman, A. L. et. al. Fusion Technology 23, no. 2 (March 1, 1993): 185–207. https://doi.org/10.13182/FST93-A30147.

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Example: General Fusion

https://youtu.be/n8qgAgyqdBM

"not if… but when"

"a race that General Fusion plans to win"

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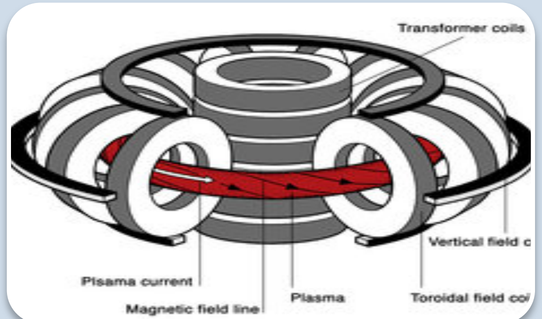
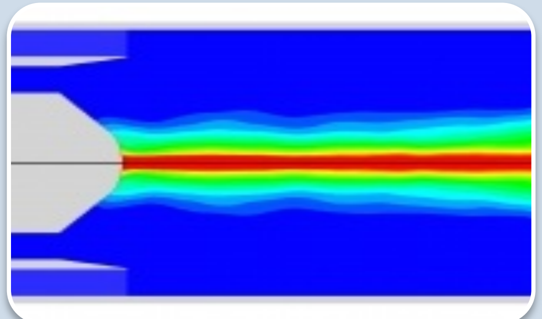
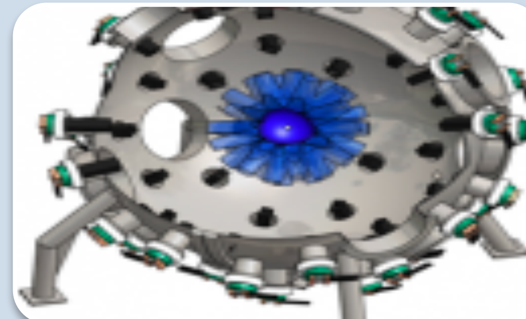
From A Few Concept Types…







Steady-state magnetic

- Magnetic
- Tokamak
- Stellarator

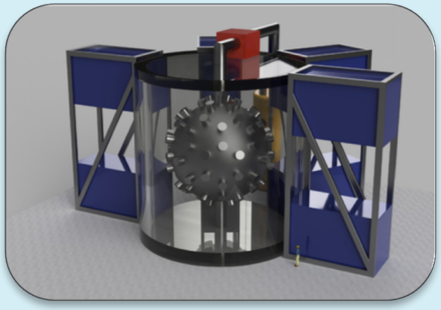
Compressed magnetic

- No external magnets!
- Z-Pinch
- Liquid liner
- Plasma liner

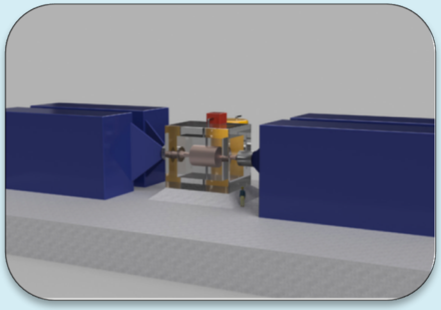
Compressed inertial

- Lasers
- Beams

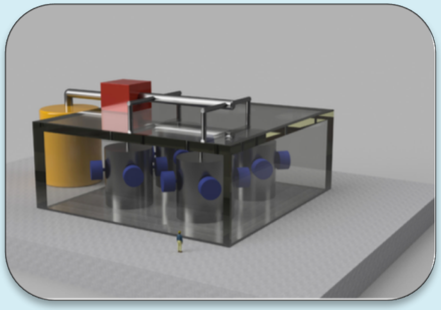
… Come A Plethora of Companies



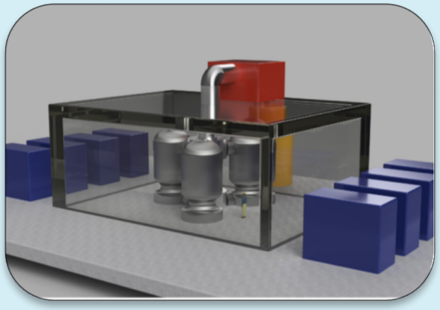
Plasma Jet Driven Magneto-Inertial Fusion (HyperV)



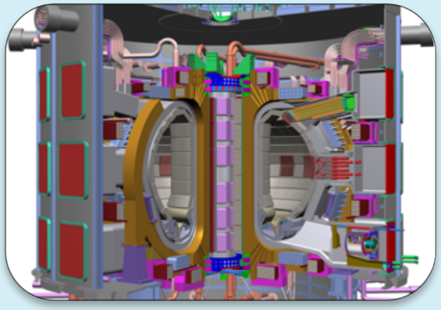
Stabilized Liner Compressor (NumerEx, LLC)



Staged Z-Pinch (MIFTI)

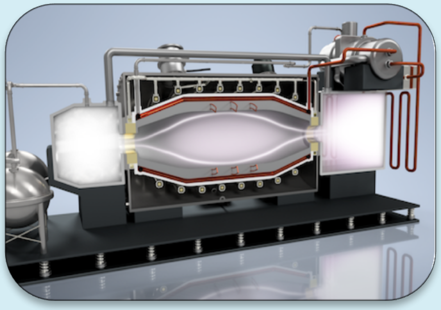


Sheared Flow Stabilized Z-Pinch (ZAP)

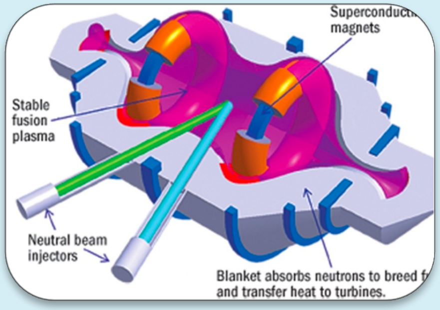


ITER (International)

SPARC (Commonwealth/MIT)



PFRC (Princeton Fusion Systems/PPPL)

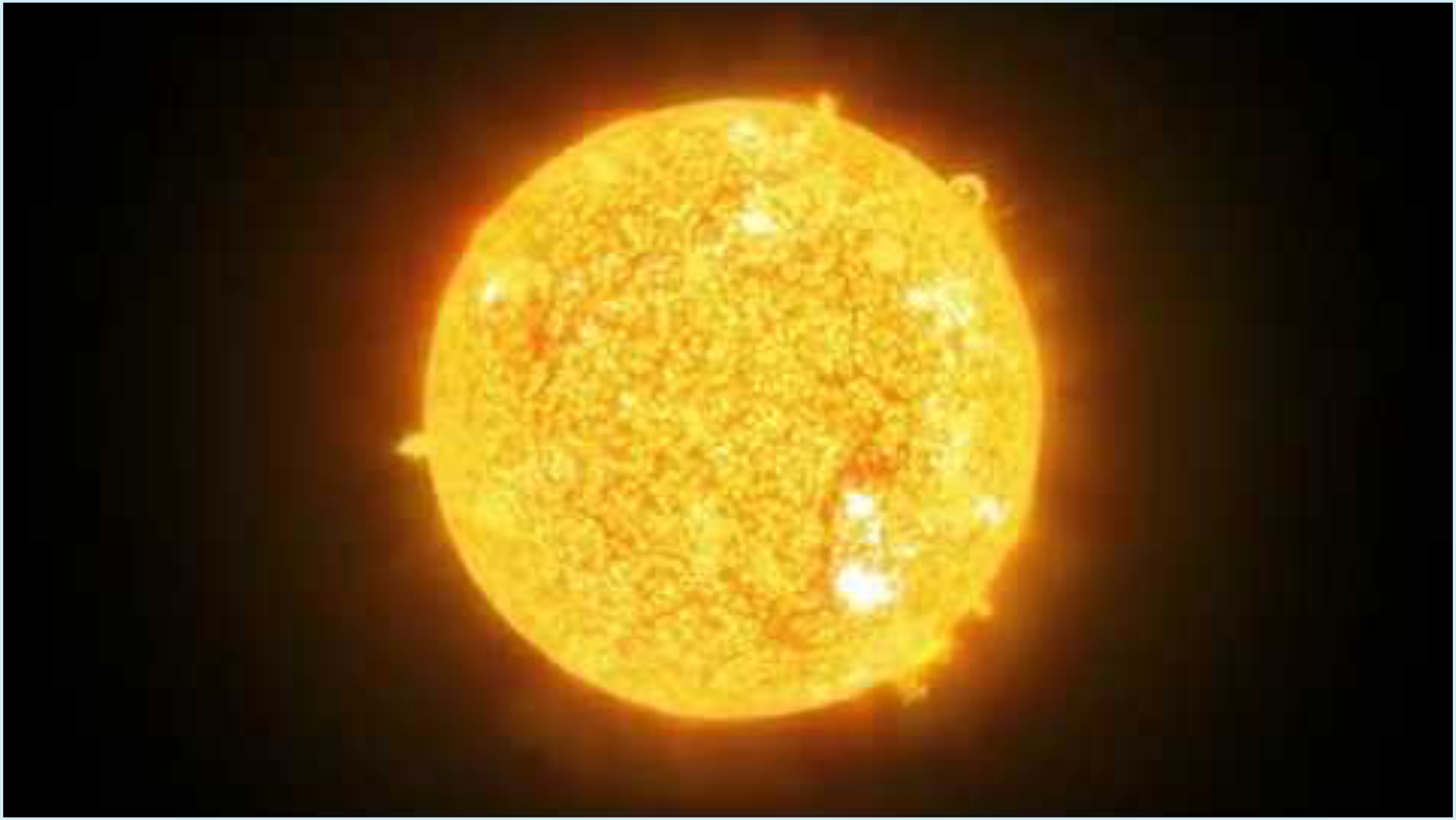


Cusp (Lockheed Martin)

Conceptual Cost Study for a Fusion Power Plant Based on Four Technologies from the DOE ARPA-E ALPHA Program, Bechtel National, Inc. Woodruff Scientific, Inc. Decysive Systems

Example: TAE Technologies

https://youtu.be/EVlWUQ-UKa4



“commercialization of fusion generators”

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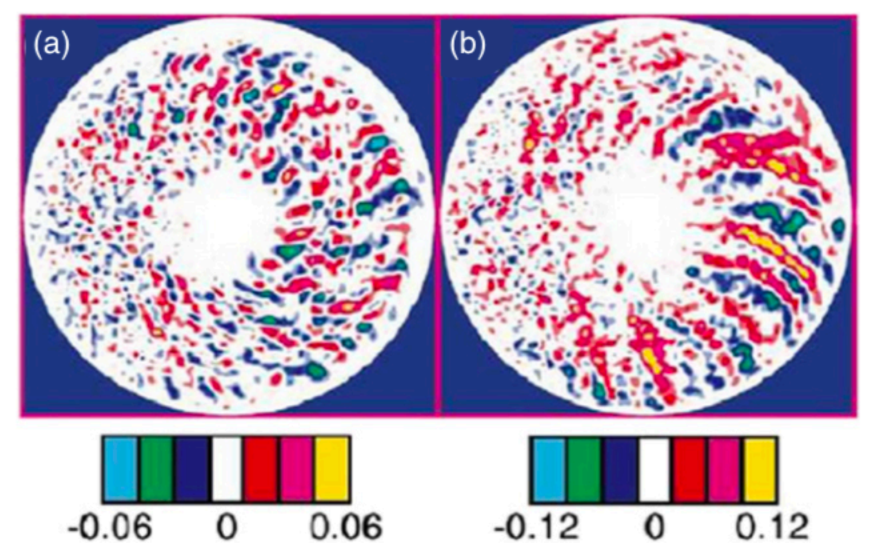
Why now? Modeling Advances

Since 1985, new models of plasma behavior have been developed

Examples are

- Gyrokinetics:
  - In 1982 a formalization was developed which allowed computers **not to resolve the orbits of electrons**, which occur billions of times per second
  - This allowed a large speedup of simulation codes
  - Gyrokinetic simulations are now used to **model turbulence in Tokamaks**
- Hybrid models:
  - Recently, models have been developed which consider **electrons to follow Magnetohydrodynamics (MHD)** while ions are fully resolved
  - This allowed a large speedup of simulation codes
  - Hybrid simulations are now used to **model instabilities in FRCs**



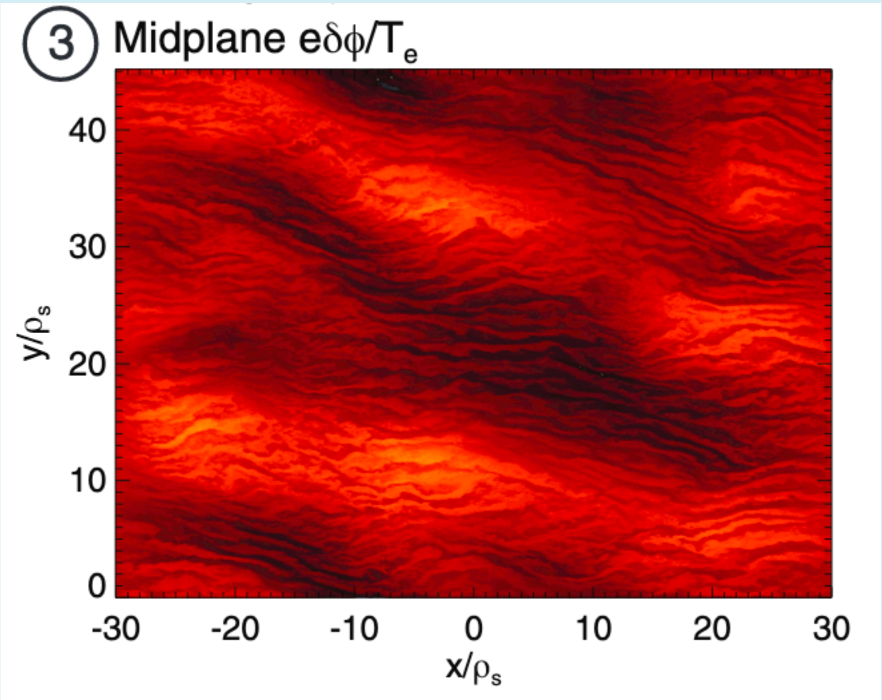
A gyrokinetic simulation showing turbulent plasma fluctuations which cause the transport of particles and energy from a tokamak core

*Lin Z., Hahm T.S., Lee W.W., Tang W.M. and White R.B. 1998 Science **281** 1835 doi.org/10.1126/science.281.5384.1835*

Why now? Computing Advances

Moore's law

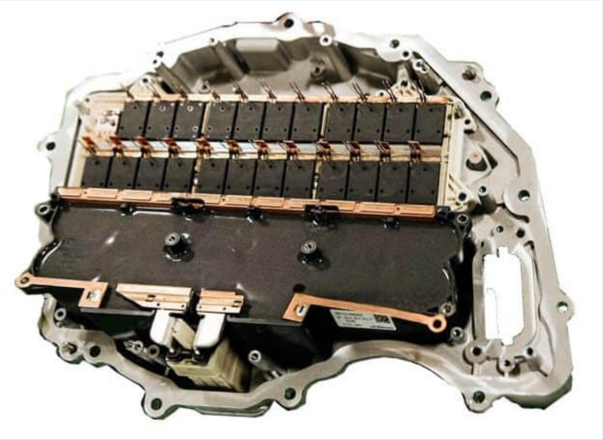
- For all the talk of Moore's law slowing down, computers today are incomparably **powerful** compared to those in 1985 when the first ITER design was written
- National labs offer computer clusters (ex: Berkeley's NERSC, 30 petaflops) to researchers and companies
- **Cloud computing** provides CPU hours as a commodity
- Graduate students can reasonably expect 10 million CPU-hours for a project, with 10,000 cores available concurrently



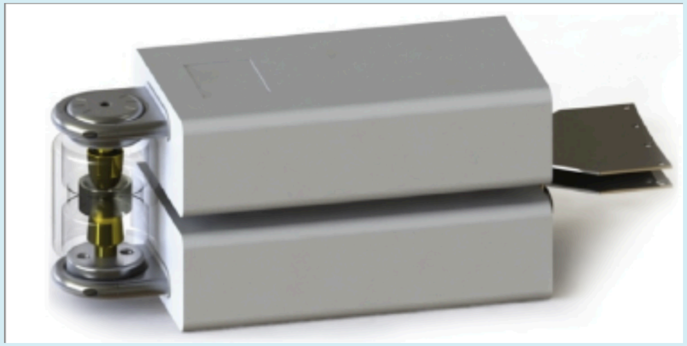
*This simulation of plasma fluctuations took **20 million CPU-hours** at NERSC*
Howard, N. T., C. Holland, A. E. White, M. Greenwald, and J. Candy. Nuclear Fusion 56, no. 1 (December 2015): 014004. https://doi.org/10.1088/0029-5515/56/1/014004.

Why Now? Hardware Advances: Power Electronics

- Other markets have prompted development of efficient power conversion
  - Portable electronics, for fast battery charging
  - Electric vehicles, for increased range and efficiency
  - Renewable energy (wind, hydro) for conversion up to grid voltages
- Two new semiconductors are used for switching power supplies, Gallium Nitride (GaN) and Silicon Carbide (SiC).
- Pulsed power is suddenly cheaper, lighter, more efficient, and faster than ever before
- Another example: Linear Transformer Driver (LTD), recently developed, have 100 ns rise time for faster pulses



SiC switches in the inverter of a Tesla Model 3
https://www.pntpower.com/tesla-model-3-powered-by-st-microelectronics-sic-mosfets/

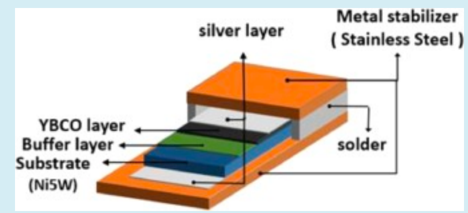


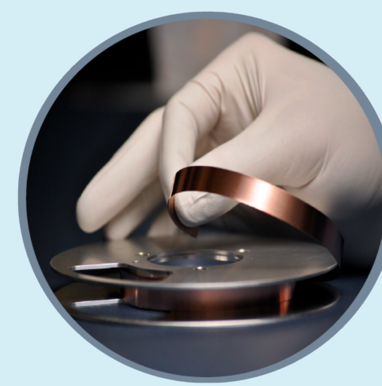
One LTD, developed in Russia for research purposes

Why Now? Better Superconductors

- Most (but not all) technologies rely on magnets
- Superconductors have become widely commercially available since ~1970
  - Think: MRI machines
- New "high-temperature" superconductors can achieve much higher fields
  - Higher fields can mean smaller fusion machines
  - Issue: the "wires" are really "tapes"
  - Issue: asymmetries in current
  - Issue: complex manufacturing
  - **Lower cost? Not yet!**

YBCO – brittle ceramic





YBCO "coated conductor" tapes

Why now? Economic Changes

- 1900s: New energy technology competes with **giant GWe plants**: Coal, fission, gas.
  - Maximize profits through economy of scale. **Bigger is better**.

Power capacity was once purchased in units of gigawatts (GW), enough to power entire metro areas

- 2000s: New energy technology competes with **small 10MWe renewables**: Windmill, solar farms.
  - Maximize profits through minimal financing and overnight capital cost. **Smaller is better**.

Modern power capacity is purchased in units of megawatts (MW), 1000x smaller than GW

ARPA-E, “Changing What’s Possible”

- Created by Congress in 2007 to enhance US’s energy security:
  1. Reduce imports
  2. Reduce emissions
  3. Improve efficiency
- First appropriations of $400M in 2009 (ARRA)
- Approximately $2B spent to date on energy projects
- Requires “cost-share” and T2M effort

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Why now? New Government Programs

*"Technologies that enhance fission, **fusion** or materials specifically for safe nuclear power generation."* OPEN 2018

ALPHA 2014 $32M
- magneto-inertial fusion (MIF), pulsed; 9 teams

OPEN 2018 $11M
- Fusion added as a topic for the first time; 3 awardees

INFUSE 2019 ~ $2M
- DOE's FES offers public-private partnerships; 12 grants to 5 companies

DIAGNOSTICS 2019 $7.2M
- Awards to build "travelling" diagnostics. 8 teams.

BETHE 2020 $30M
- Fusion-specific program

*"The U.S. has an opportunity to seize **global leadership** in this transformational energy sector and attract global industry stakeholders by building on the Department's laboratory capabilities and **world class fusion science** talent while partnering with these private fusion companies."* US Senate, Report 116-102

Fusion Research Ecosystem

~$B Mainstream Government Efforts

- US DOE FES
- ITER collaboration
  - EU, India, Japan, China, Russia, South Korea, USA
  - >$40B
- Research Tokamaks (6)

~$100M Private Companies

- TAE Technologies
- Commonwealth Fusion Systems
- Tokamak Energy (UK)
- General Fusion (Canada)
- Lockheed Martin

~$10M ARPA-E Support

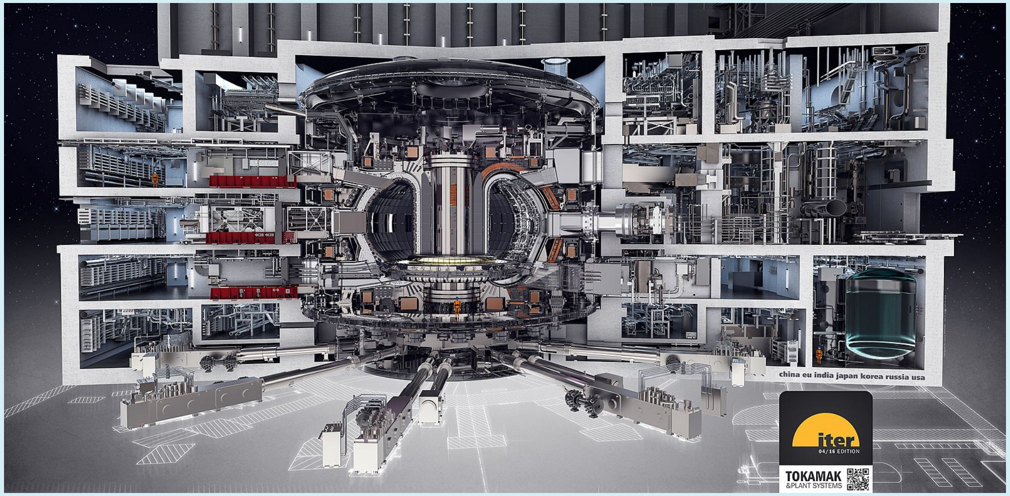
- Helion
- Princeton Fusion Systems
- CT Fusion
- Zap Energy / FuZE
- MIFTI
- Hyper V / Hyper Jet

Other private

- ENN (China)
- Lawrenceville Plasma Physics
- First Light Fusion (UK)
- Proton Scientific
- Compact Fusion Systems
- Helicity Space

Big Government Efforts

- US Department of Energy, Office of Fusion Energy Science: ~$600M per year budget
- ITER: ~$3.5B per year budget (fusion expected 2035)
- National programs, including the world's biggest Tokamaks:
  - D-IIID (USA)
  - JET (UK)
  - ASDEX (Germany)
  - EAST (China)
  - KSTAR (South Korea)
  - JT-60 (Japan)
- Wendelstein 7-X
  - "Stellarator," not tokamak
  - Germany
- NIF
  - USA, laser inertial fusion



Rendering of ITER, including tiny people. Top to bottom is 6 stories

Credit: ORNL, under CC Attribution 2.0 Generic license

Privately Funded Efforts, ~$100M

Company	Country	Confinement name	Approx. funding	Notable funding sources	Notable details
TAE Technologies	USA	Field-reversed configuration (FRC)	$700M	Sovereign wealth, Paul Allen, Goldman Sachs	Targeting p-^{11}B fusion
Commonwealth Fusion Systems	USA	HTS Tokamak	$115M	Gates	Spun out: MIT
Tokamak Energy	UK	HTS Tokamak	$65	VCs	Spun out: Culham lab
General Fusion	Canada	Piston compressed	$127M	Bezos, Canada	
Lockheed Martin	USA	Inflated spindle cusp	~$100M	Internal	

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DOE's ARPA-E Funded Companies, <$20M

Company	Confinement name	Approx. funding	Notable funding sources	Notable details
Helion	Magnetically Compressed FRC	$17M	ARPA-E, Thiel, Y Combinator	
Princeton Fusion Systems	FRC	$3M	ARPA-E, NASA	Us! PPPL
CT Fusion	Spheromak	$4M	ARPA-E	U of Washington
Zap Energy / FuZE	Z-pinch	$14M	ARPA-E	U of Washington
MIFTI	Z-pinch	$4M	ARPA-E	UC Irvine
Hyper Jet / Hyper V	Jet Compressed CT	$30M?	ARPA-E ($8M), NASA	

Small Private Ventures

Company	Country	Confinement name	Notable funding sources	Notable details
ENN	China	FRC and Tokamak	Internal	Amount undetermined
Lawrenceville Plasma Physics	USA	Dense Plasma Focus	Crowd funded	
First Light Fusion	UK	Inertial Confinement	VCs ?	Spun out: Oxford
Proton Scientific	USA	"Relativistic Vacuum Diode"	INFUSE	
Compact Fusion Systems	USA	Compressed FRC	ARPA-E ?	
Helicity Space	USA	"Merging Plectoneme"	INFUSE	What is a plectoneme anyway?

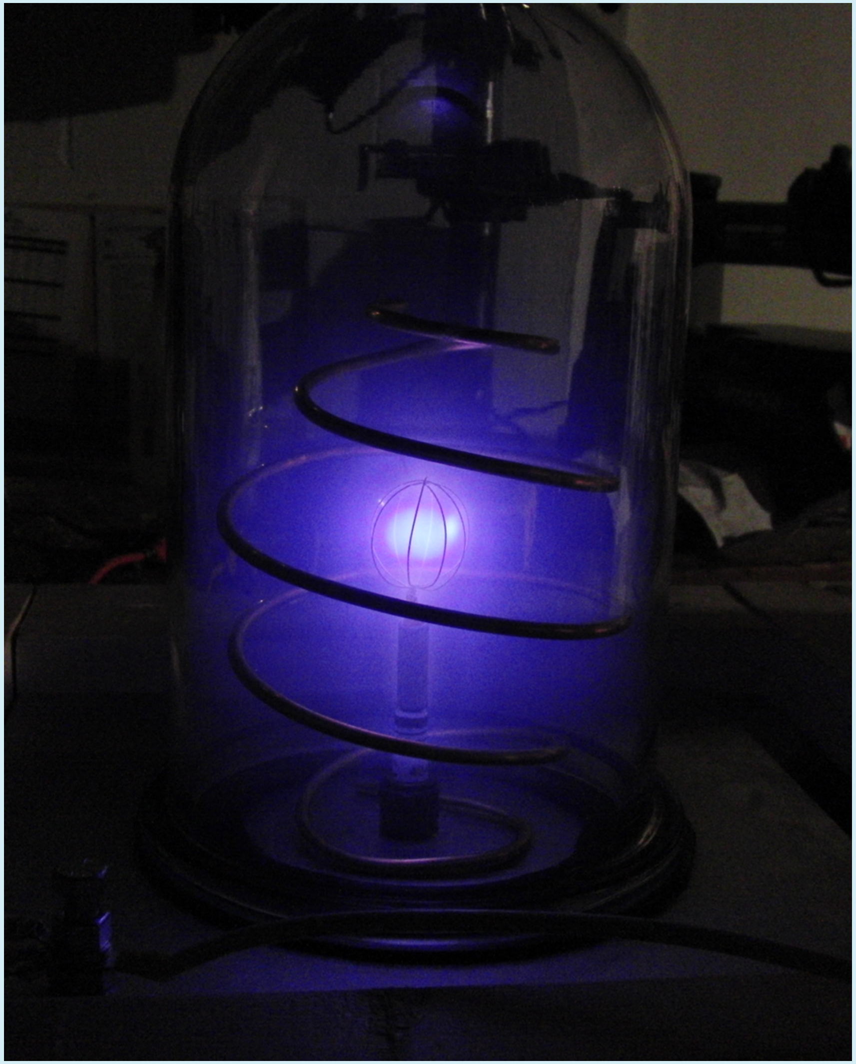
Status: Experimental

- The life cycle of a high-tech product is:
  - Research, experiment, technology development, production

- Each of these companies has at most an **experiment**. None are yet at the technology development stage!

- What to look for in the press?
  - Reactor design elements – how much power, etc.
  - Is the predicted date of success sufficiently far in the future?
  - The goal: performance demonstration

Hype or Savvy: Neutrons?



Wikipedia, William Jack's homemade fusor

Claim: "Our technology produced neutrons, so it works!"

- A high school student can build a fusor that makes neutrons, left, but it can never be a power plant
- Neutrons only mean that some portion of the ions are hot
- It doesn't mean that the design has solved the engineering problems associated with neutrons
  - Neutrons cause damage!

Hype or Savvy: Commercial Power in 5 Years?

Lesson: Engineering projects take ***time***, even when the physics is well known.

1. Rivian, https://rivian.com/
   - Founded in 2009 to make an electric truck
     - This does not require any new physics
   - First product: 2021
2. SpaceX, spacex.com
   - Founded in 2002 to make new rockets
     - This also does not require new physics. See: Apollo
   - First Falcon 9 launch: 2011
3. Pharmaceuticals
   - Takes on average 12 years from drug invention to market
   - Most fail!

Falcon 9, wikipedia

The Future of Fusion

- Expect a few winners from the current efforts
  - Tokamaks
  - Alternate configuration(s)
  - Smaller “nameplate” capacity plants
    - Competing against wind, solar, storage
- Expanded public-private partnerships
  - Government supporting the private efforts
  - Similar to NASA with new launch systems
- Expect 10-20 years for real results, **not** 5

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