The Quest for Fusion Energy – Incredible Potential, Extraordinary Challenges

By
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Presented to
General Atomics Retirees Association
San Diego, CA

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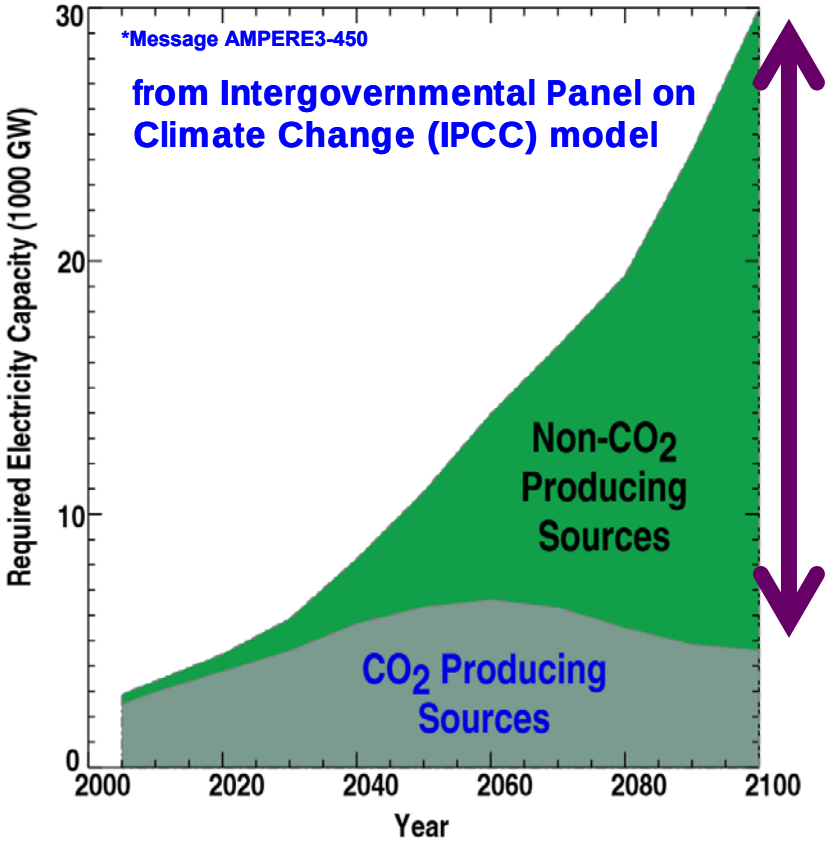
Outline of Talk

- Introduction to Energy Needs and the Potential of Fusion
- Producing Fusion Conditions on Earth
- Progress Towards Fusion Energy
- Exciting New Era for Fusion Energy Development
- Challenges in Developing in Fusion Energy
- Closing Thoughts

Exploding Energy Demand in Coming Decades Provides Significant Motivation for Urgency in Fusion Development



- **Projected need for ~ 25,000 GW from non-CO2 producing sources**

25,000 1 GW-e plants !!!

- **Consequently, annual investment in energy projected to explode**
  - $0.8 T by 2050
  - $2.5 T by 2100

→ Need is urgent and significant

Fusion is the Fundamental Process that Helped Create the Universe We Live In

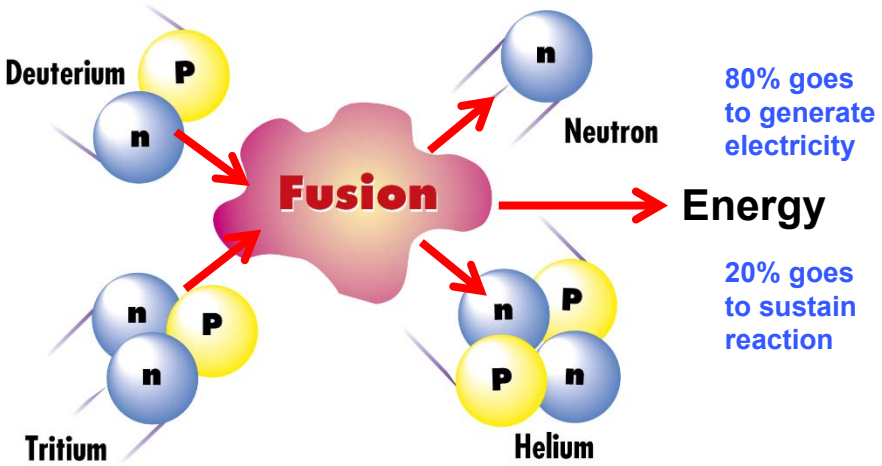
Fire: Self-sustaining chemical reaction at > 2,000° F

Fusion: Self-sustaining nuclear reaction at > 200,000,000° F

Fusion powers all the stars in the universe

Fusion – The Basics

- **In a fusion reaction, light nuclei combine to form a heavier one…**



- **Originally hypothesized in early 1920s…shown to be source of solar power in 1938 (Bethe)**

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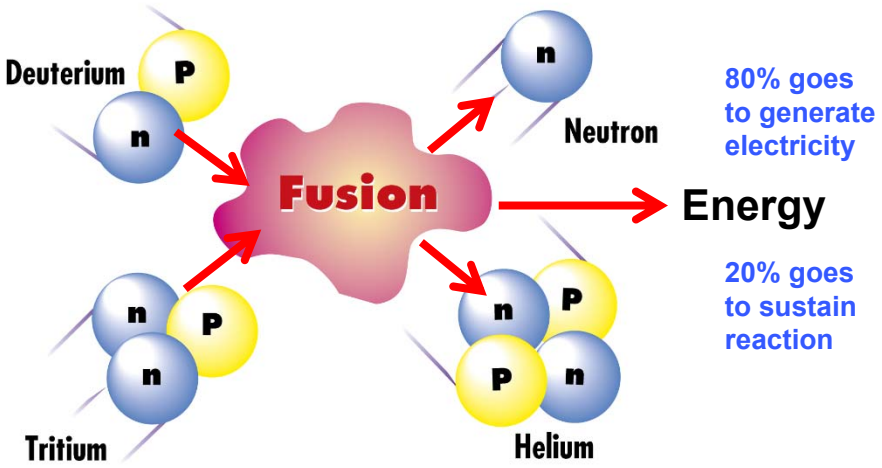
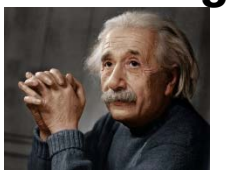
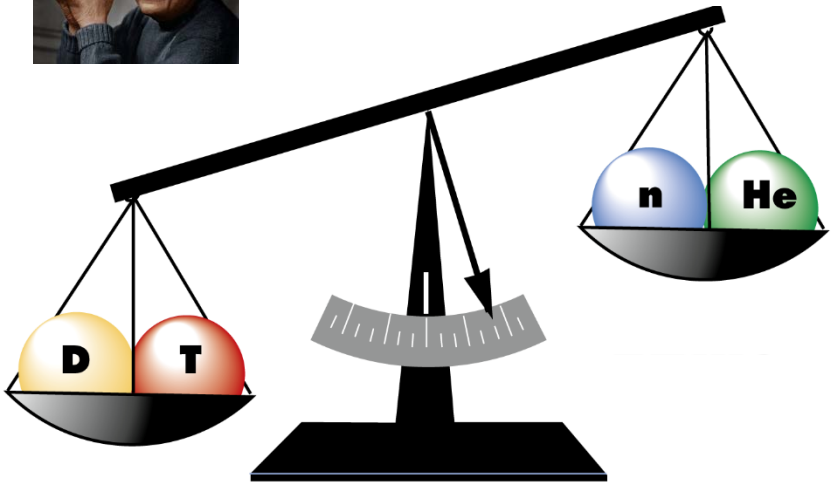


- Originally hypothesized in early 1920s…shown to be source of solar power in 1938 (Bethe)

- …Releasing large amount of energy



$\Delta E = \Delta m\, c^2$



DT Fusion: 339 GJ/g DT
Fission: 82 GJ/g U-235
Methane: 20 kJ/g CH_4

Factor of > 1,000,000

Reward of Developing Fusion Energy Is Well Worth the Risk of Investment

- **Nearly inexhaustible fuel supply. Sea water has:**
  - 60 billion years supply of deuterium
  - 30 million years supply of lithium (for tritium)
- **Clean and Safe**
  - No greenhouse gases
  - Only short-lived radioactive waste
  - No risk of runaway reactions or meltdown
  - Low risk of proliferation
- **Available to all nations**
  - Reduced conflict over resources
- **Minimal land use and available on-demand**

A Lot of Energy from a Small Amount of Fusion Fuel

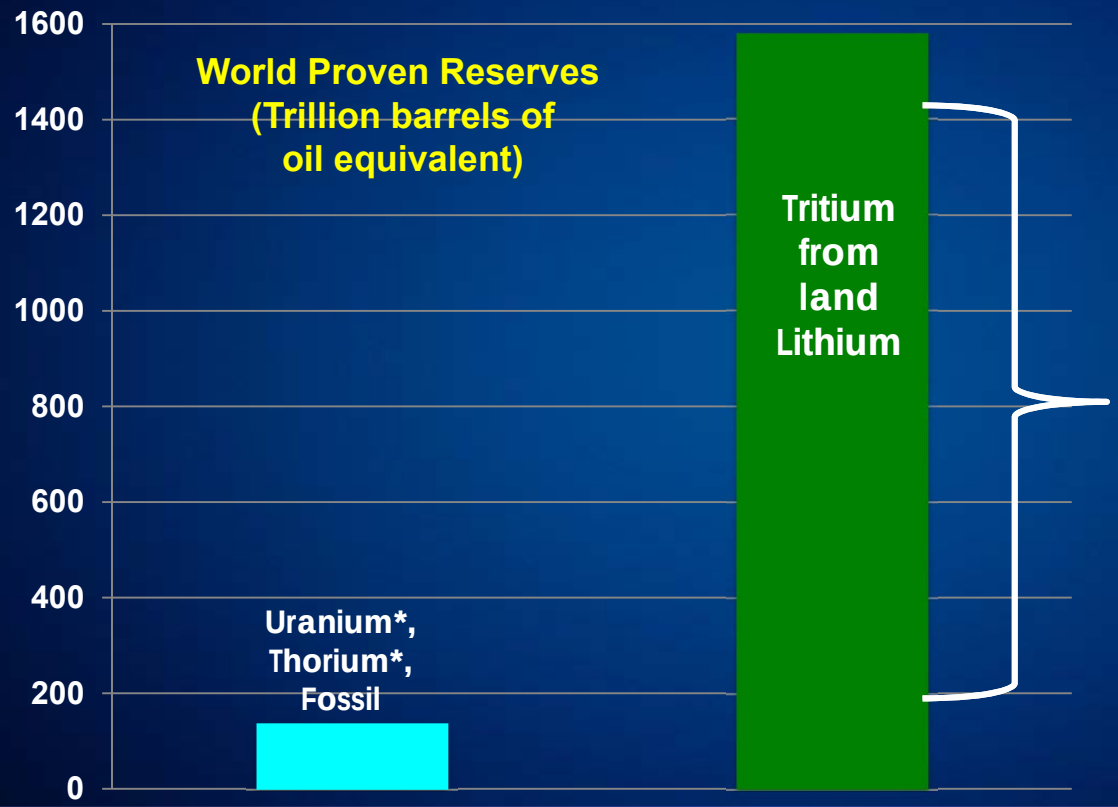
1000 MEGAWATTS ELECTRICITY FOR 1 DAY (1,000,000 Homes)

	COAL PLANT	D-T FUSION PLANT
FUEL CONSUMED	18,000,000 LB COAL *80x* 	1.0 LB D_2 + 1.5 LB T_2 
WASTE PRODUCED	60,000,000 LB CO_2 1,200,000 LB SO_2 160,000 LB NO_2  *Fills 2600x*	2.0 LB He^4 *Fills 400x* 

Huge difference in fuel required…

… and in waste produced

World's Lithium Reserves Hold 12X More Energy than ALL Uranium*, Thorium*, Coal, Oil and Natural Gas Supplies



Can meet Global energy needs for *over 16,000 years* at current rates of consumption

* When used in a fast closed cycle reactor

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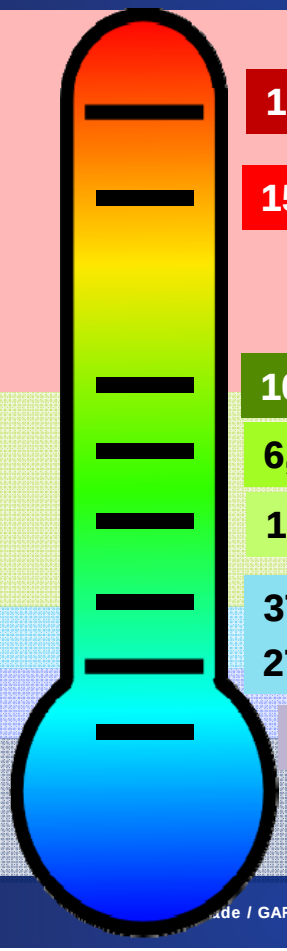
Fusion in the Laboratory Requires Temperatures Greater than the Sun



Plasma

100,000,000° K → Fusion!!!

15,000,000° K → Center of Sun

Gases

100,000° K → Atoms Lose Electrons

6,000° K → Surface of Sun

1,800° K → Iron Melts

Liquids

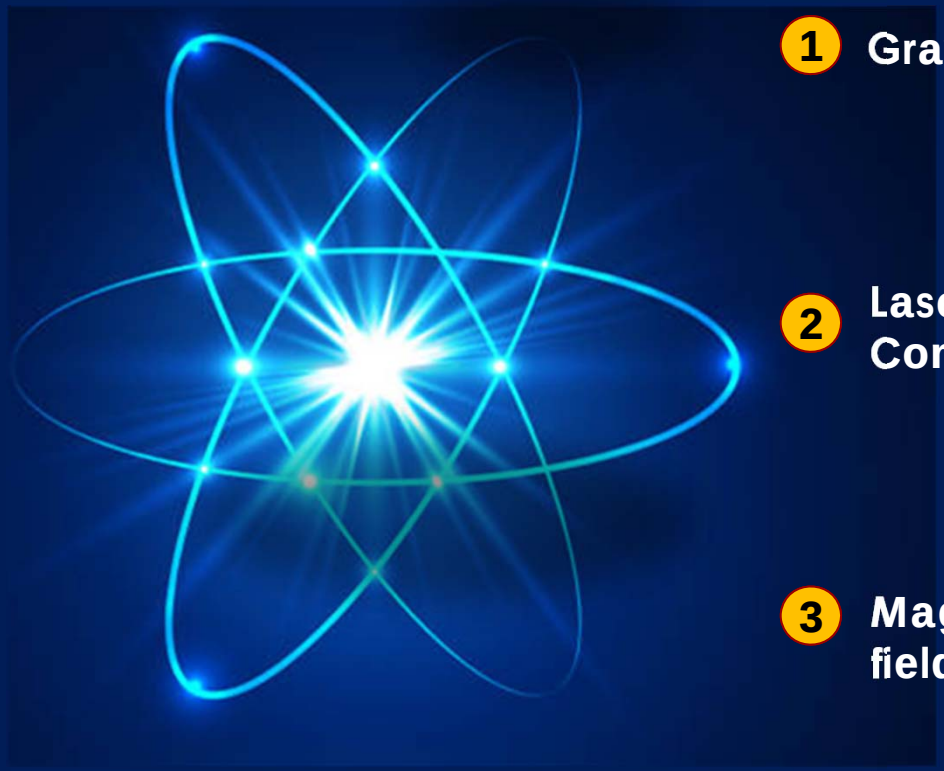
373° K → Water Boils

Solids

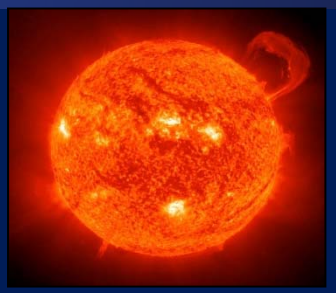
273° K → Ice Melts

0° K → Absolute Zero

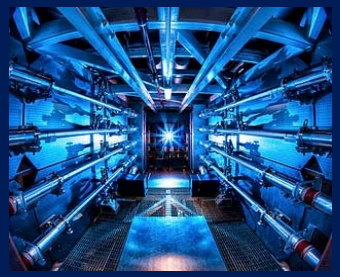
Three Known Ways to Generate Fusion Conditions



1. **Gravity**
2. **Laser Compression**
3. **Magnetic fields**



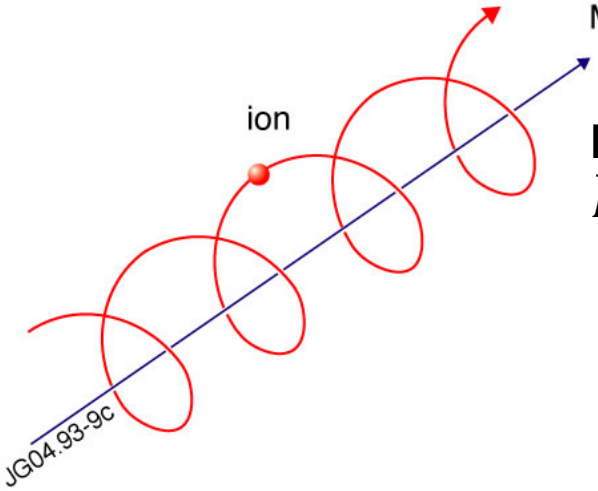
Sun and stars



National Ignition Facility (LLNL)

DIII-D (San Diego)

Magnetic Confinement Takes Advantage of Natural Interaction of Charged Particles with Magnetic Fields



Lorentz force: $\vec{F} = \vec{v} \times \vec{B}$

Charged particles follow magnetic field lines

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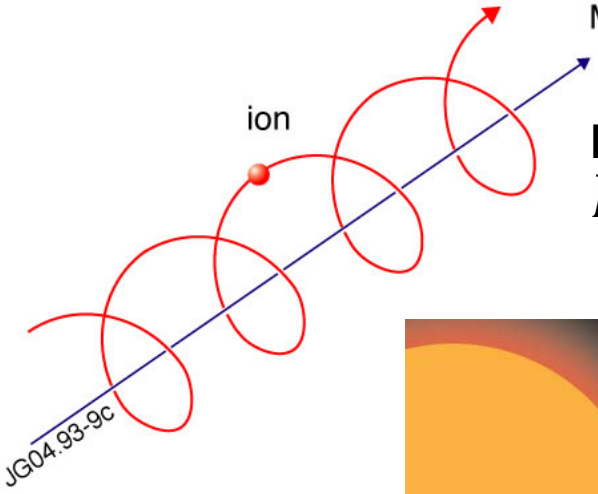

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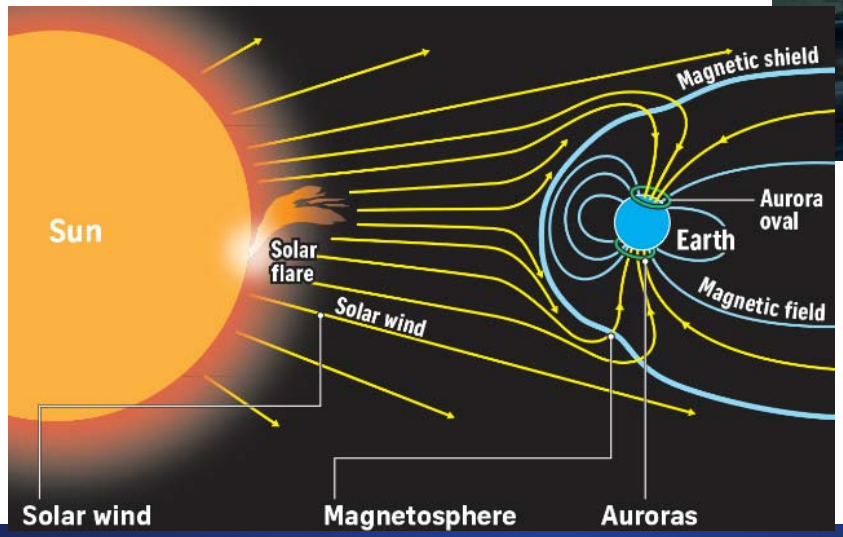

Example: High energy charged particles follow magnetic field lines to polar regions

→ Northern lights

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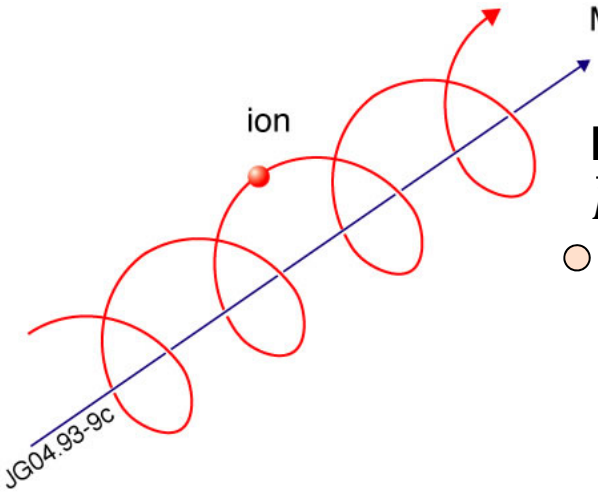
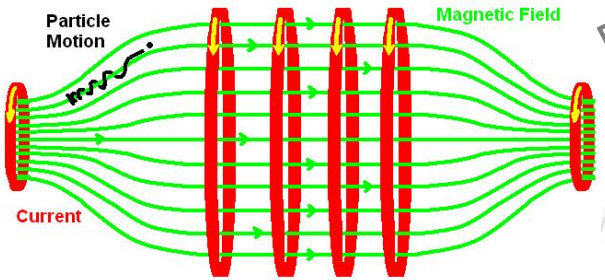


Lorentz force: $\vec{F} = \vec{v} \times \vec{B}$

Make a magnetic bottle and charged particles can be confined to a small volume (and heated)!!

Lots of Ideas on the Best "Magnetic Bottle" – Tokamaks Have Emerged as the Best Performing

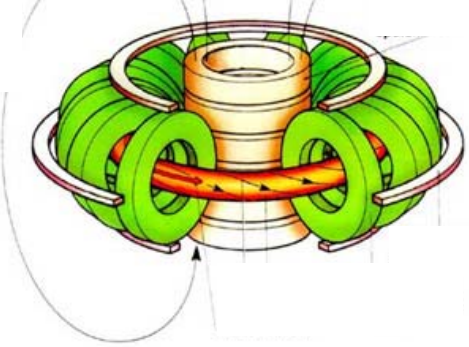
Mirror



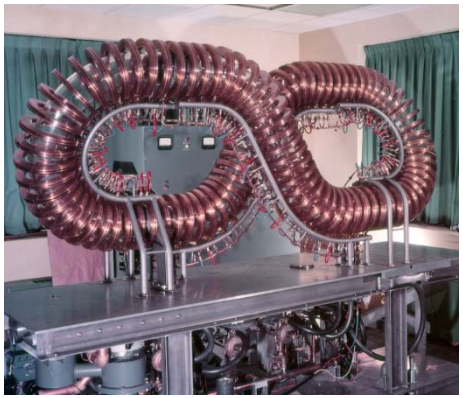
Reversed Field Pinch

Tandem Mirror

Tokamak



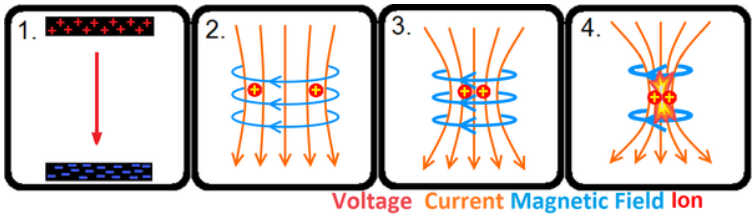
Stellarator



Merging FRC

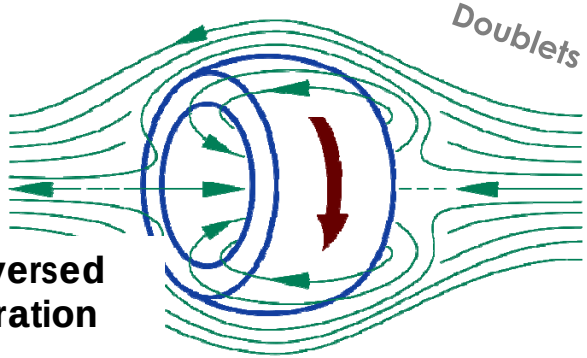
Spheromak

Pinch



Magnetic Cusp

Doublets



Field Reversed Configuration

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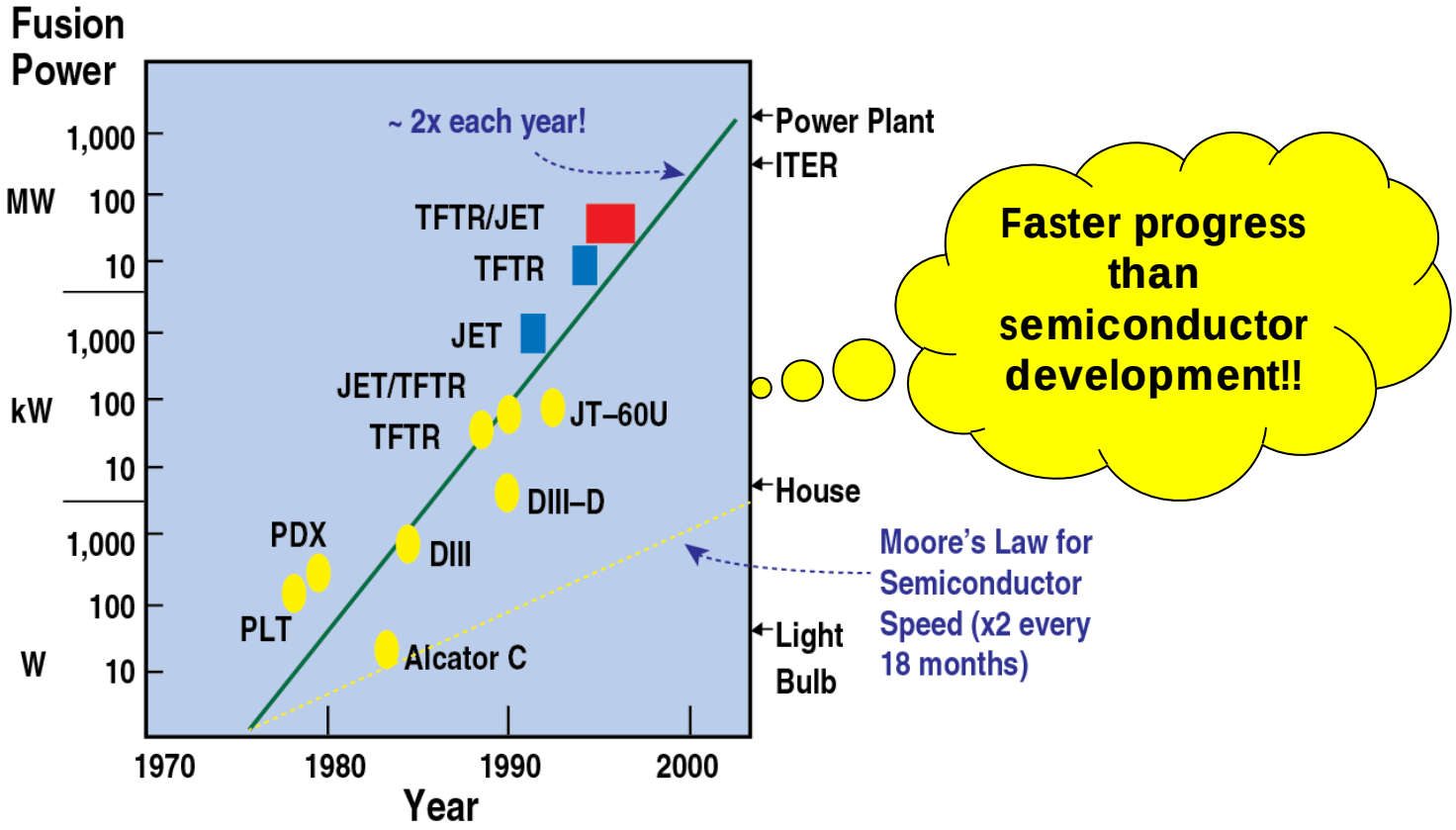
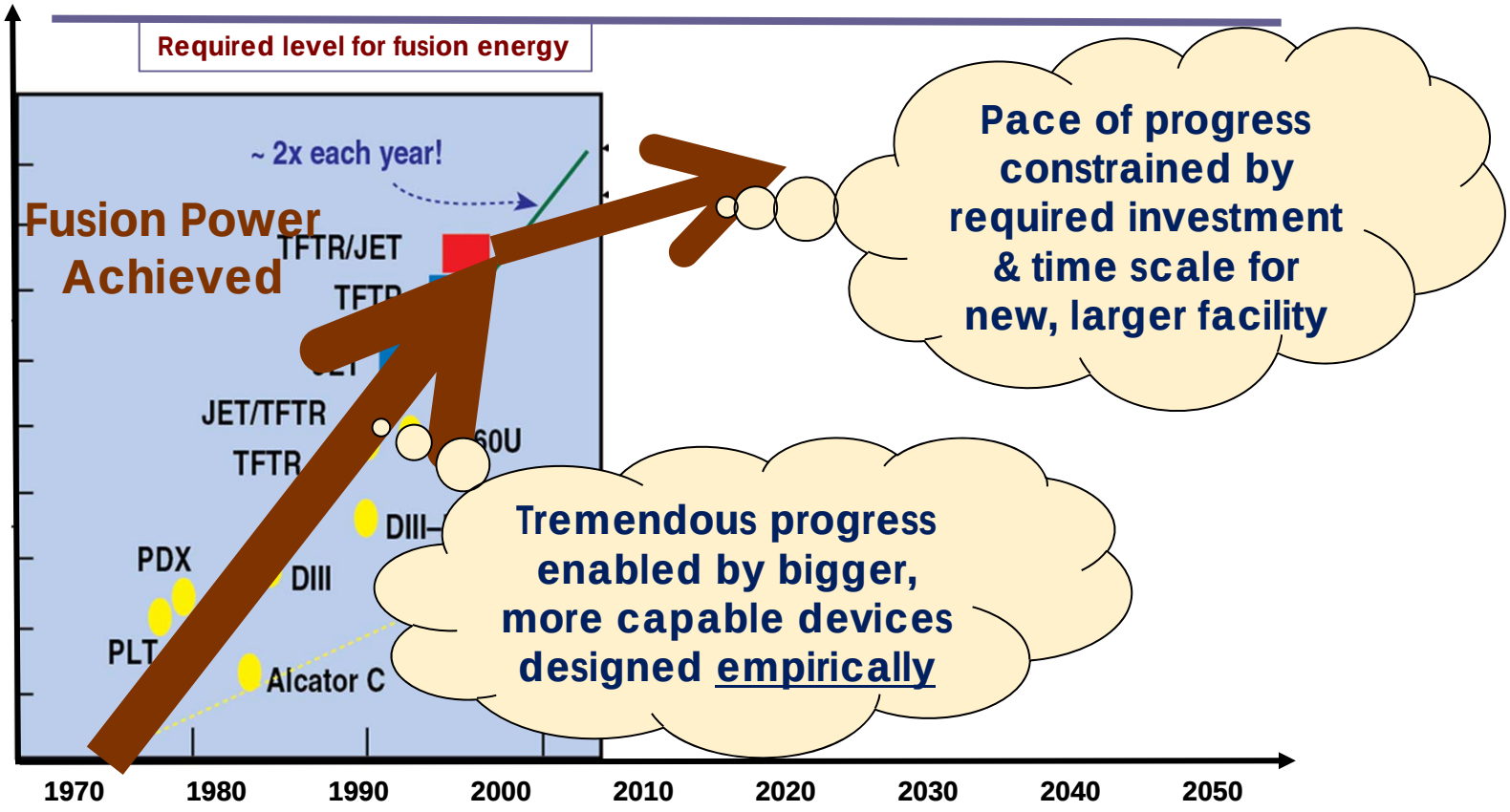
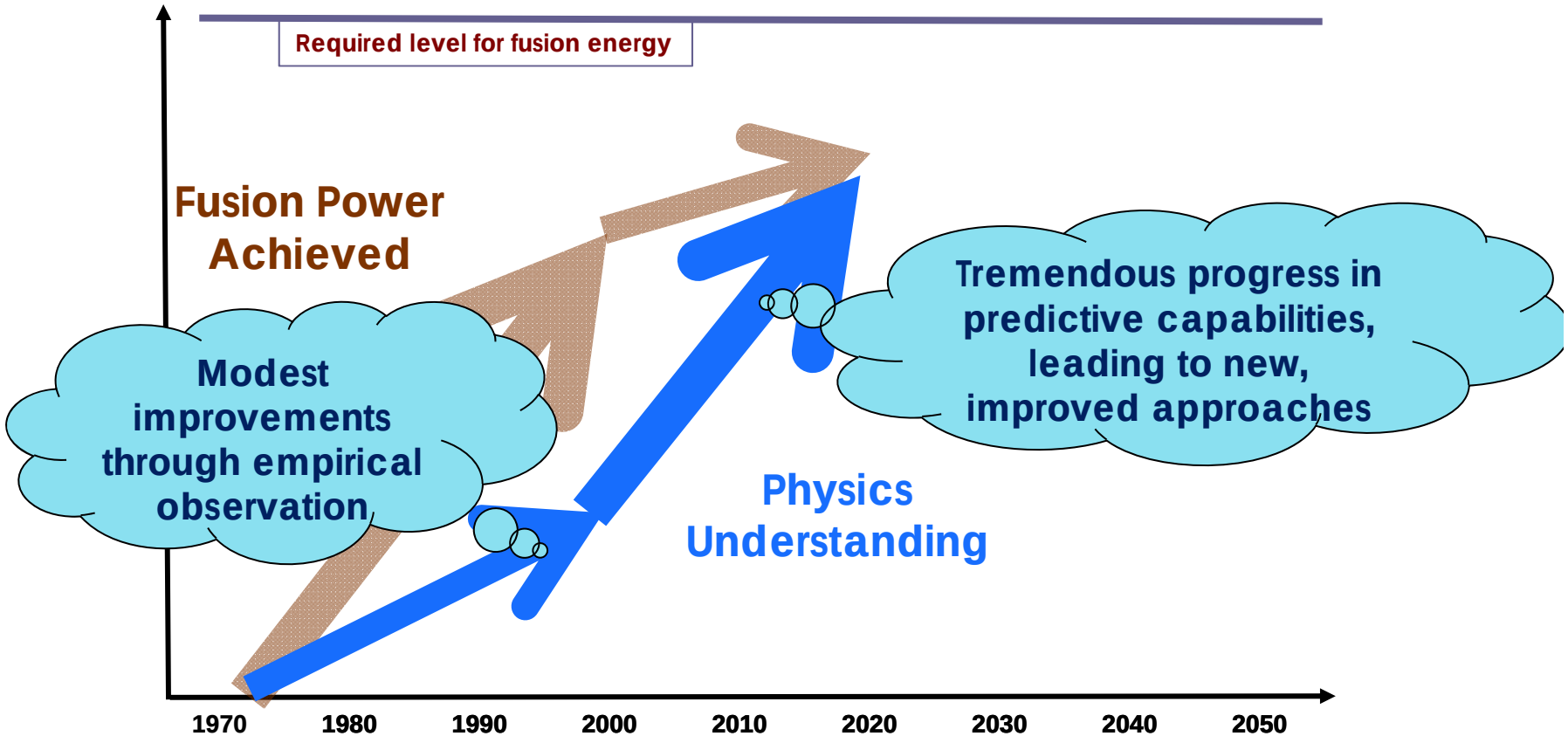
During the Late 20th Century, Tokamak Progress Towards Producing Fusion Power Was Impressive



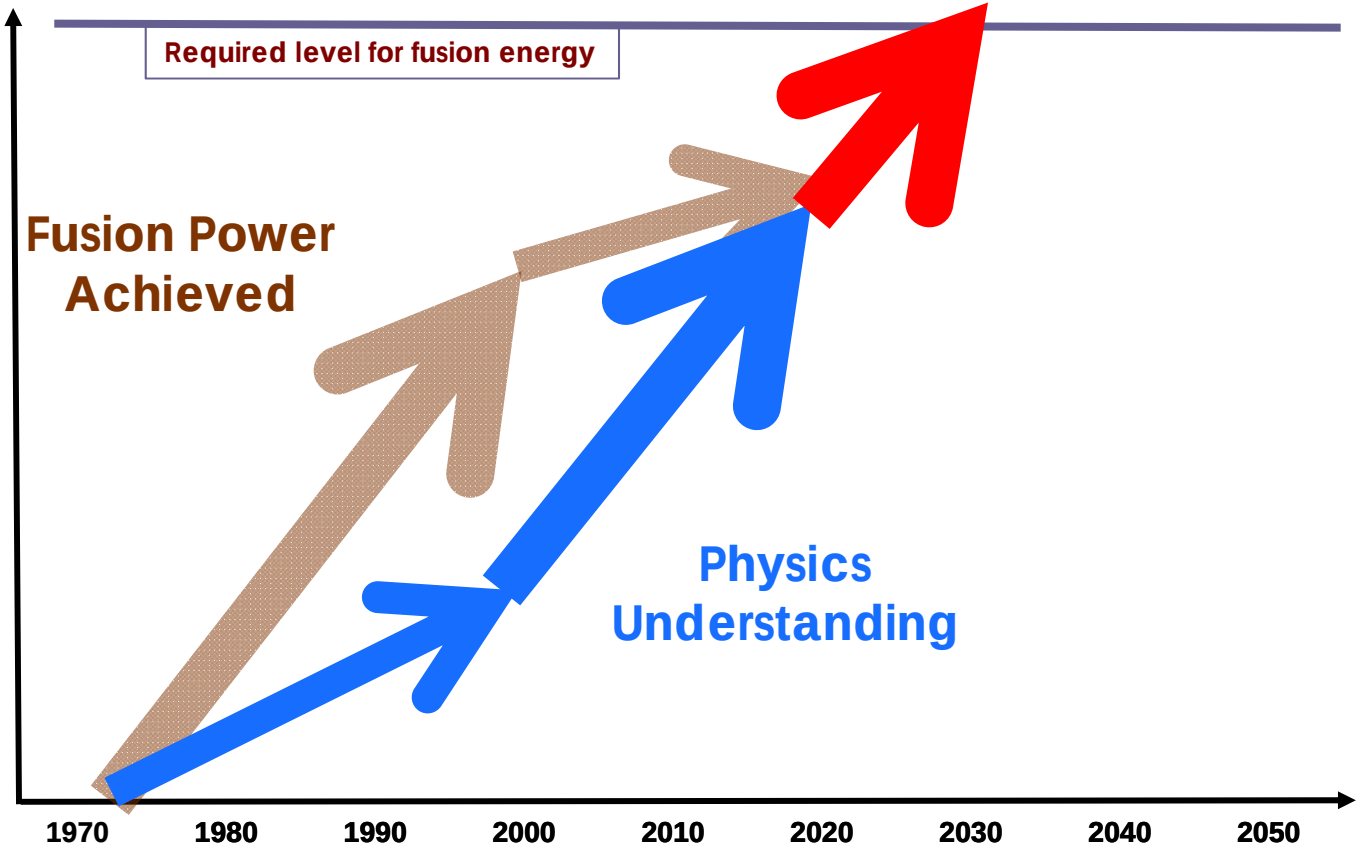
Early Rapid Progress Fueled by Ability to Increase Facility Size …Until a Limit was Reached



Lull in Progress Towards Fusion Energy Goal Accompanied by Tremendous Advances in Physics Understanding



Can We Leverage New Capabilities to Accelerate the Timeline?



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The National Academies Says “Yes”

“Now is the right time for the United States to develop plans to benefit from its investment in burning plasma research and take steps towards the development of fusion electricity for the nation’s future energy needs.“

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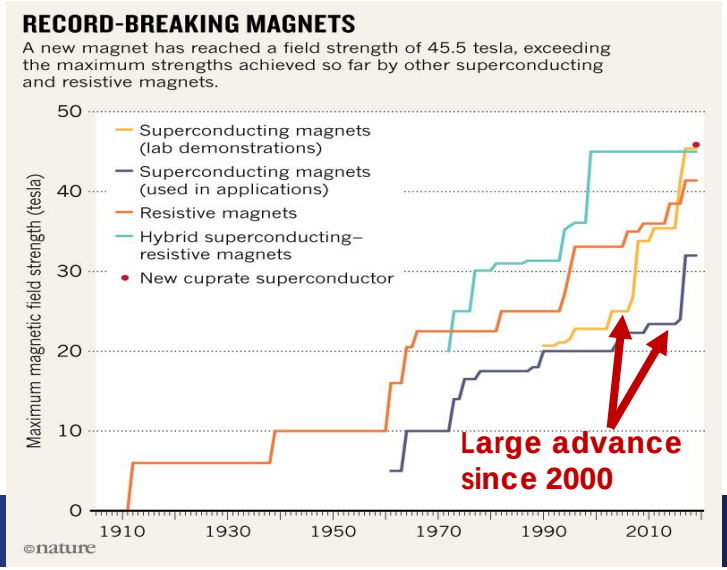
Why such an aggressive statement?

A Confluence of Developments Have Positioned Fusion Development for a Major 20-year Push

Recent Developments:

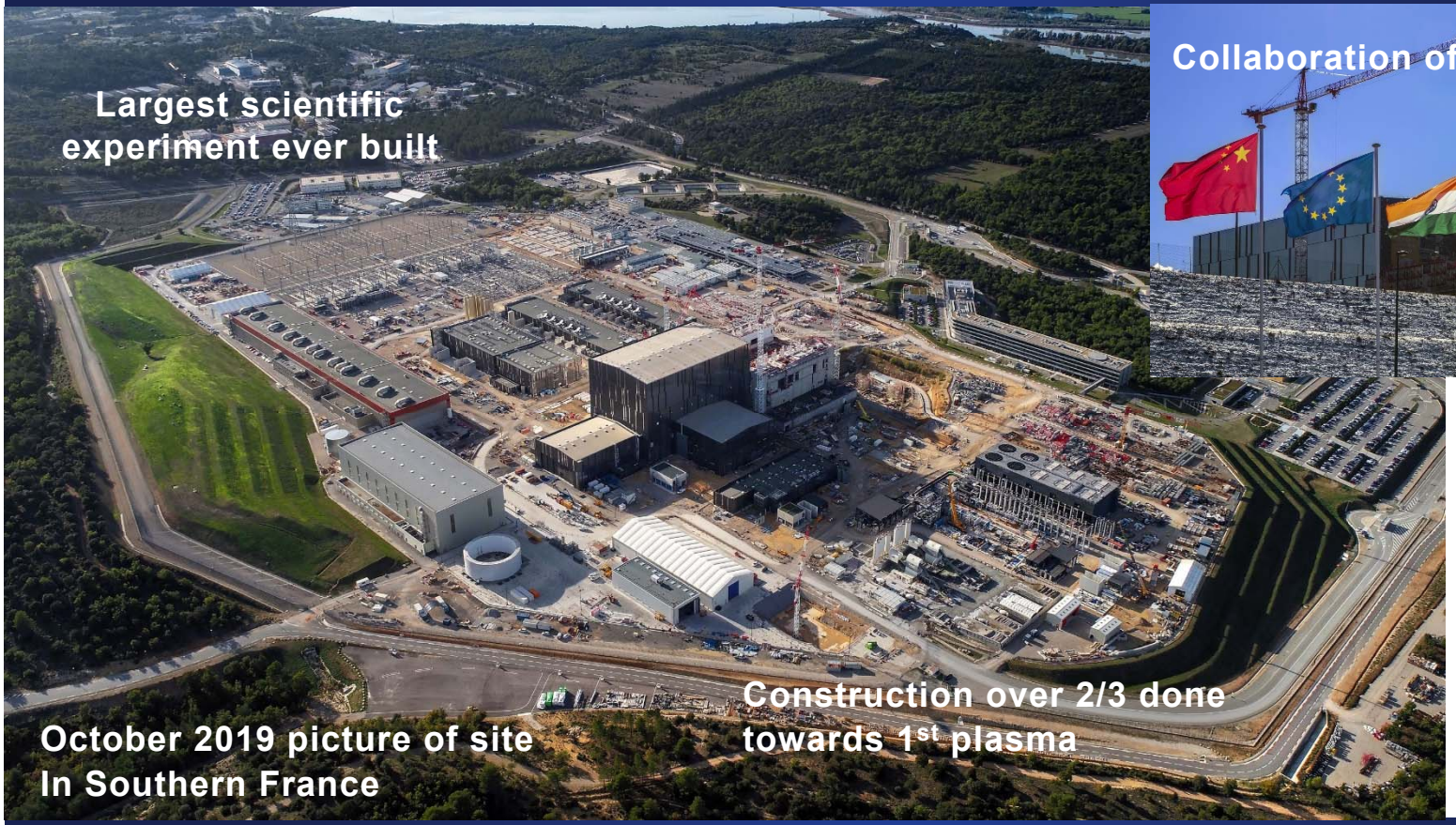
- **ITER project progressing rapidly**
- **Extensive predictive tools for optimizing performance now in place**
- **Availability of new technologies to address key challenges**
  - Superconductors, Materials by Design, Advanced Manufacturing Techniques
- **Significant escalation in investment in clean energy → new $$$ to make push possible**

Simulation of Turbulence



ITER is on the Horizon

ITER – A International Partnership to Demonstrate the Scientific and Technological Feasibility of Fusion Energy



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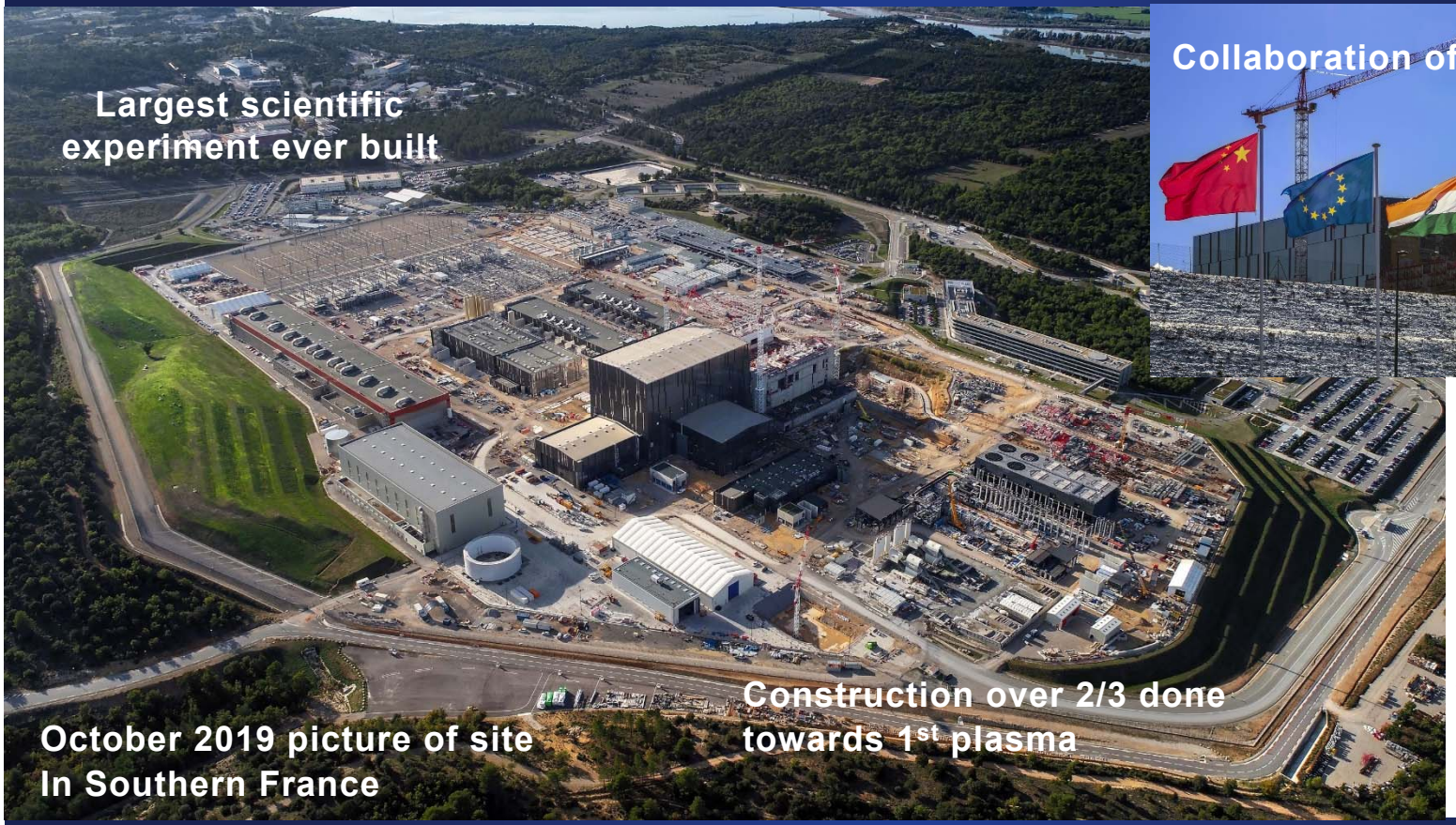

- Designed to produce 500 MW for 400 s
- 1st operations in 2025
- Fusion power demonstration in mid 2030s

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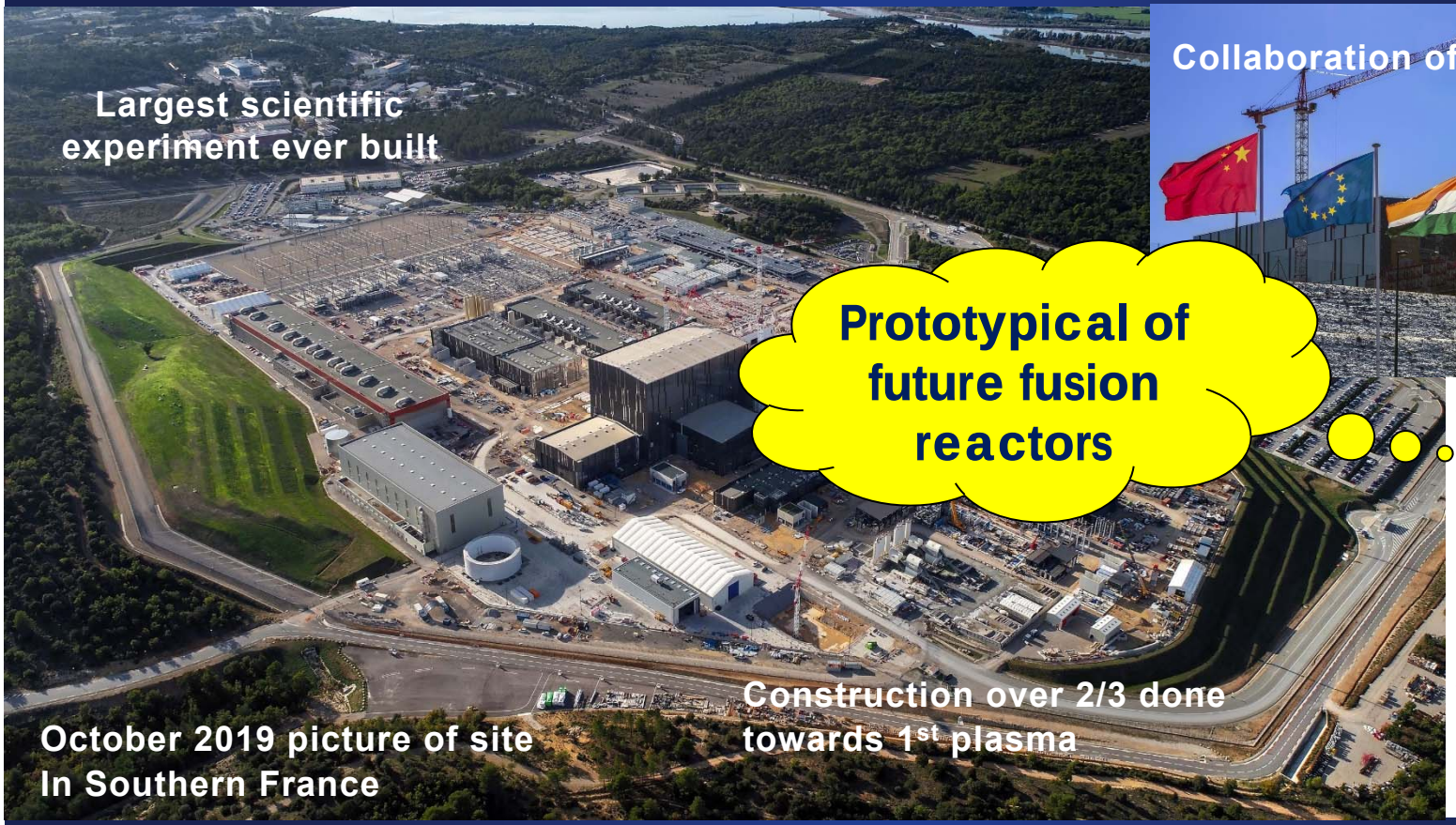
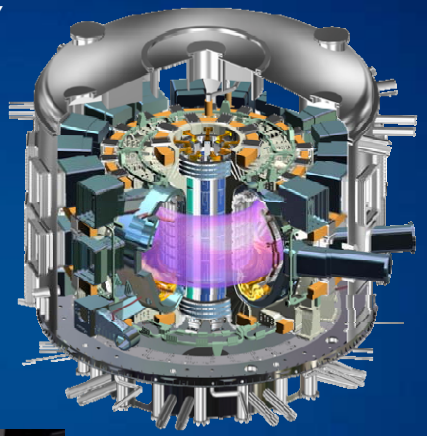


Prototypical of future fusion reactors

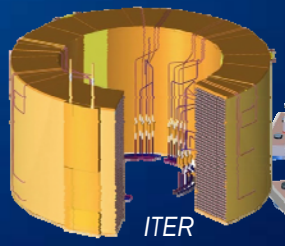
- **Designed to produce 500 MW for 400 s**
- **1st operations in 2025**
- **Fusion power demonstration in mid 2030s**

A Major Component of ITER is Being Built by General Atomics in Poway → the World's Most Powerful Pulsed Electromagnet

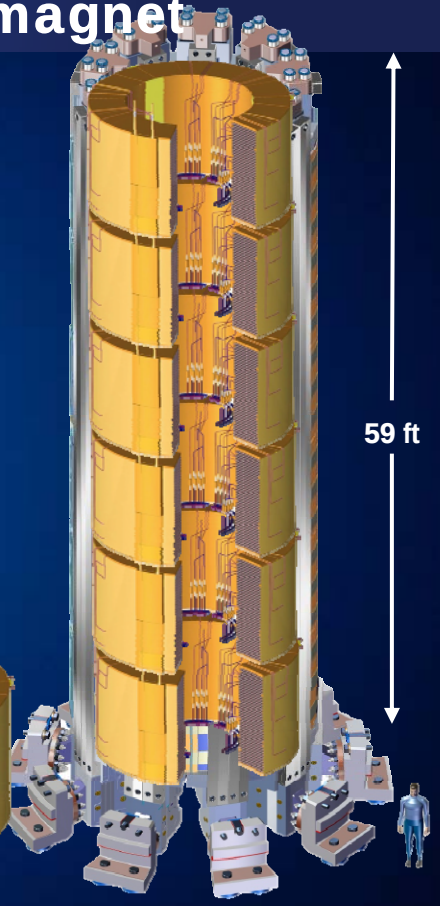
GA ITER Central Solenoid Facility

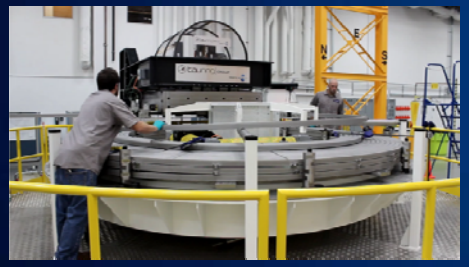


ITER



ITER Magnet





Magnet winding process

Each module has over 3.5 miles of conductor and weighs 250,000 lbs

Automated Insulation of Coil (180 miles per module)

Recent Years Have Seen A Significant Increase in Investment and Interest in Fusion Energy by the Private Sector

- **$1B of investment in last 5 years**
- **Leveraging DOE programs through cost-share programs**
- **Have established industry trade group to promote common interests**

Helion Energy
COMMONWEALTH FUSION SYSTEMS
generalfusion
tae TECHNOLOGIES
fuse
tokamak energy
a faster way to fusion
CTFusion
HYPERJET FUSION CORP
MIFTI
COMPACT FUSION SYSTEMS
LPP FUSION
PROTON SCIENTIFIC
HORNE TECHNOLOGIES
first light
AGNI FUSION ENERGY
PrincetonSATELLITE SYSTEMS
EMC2
RENAISSANCE FUSION
FUSION INDUSTRY ASSOCIATION
HelicitySpace

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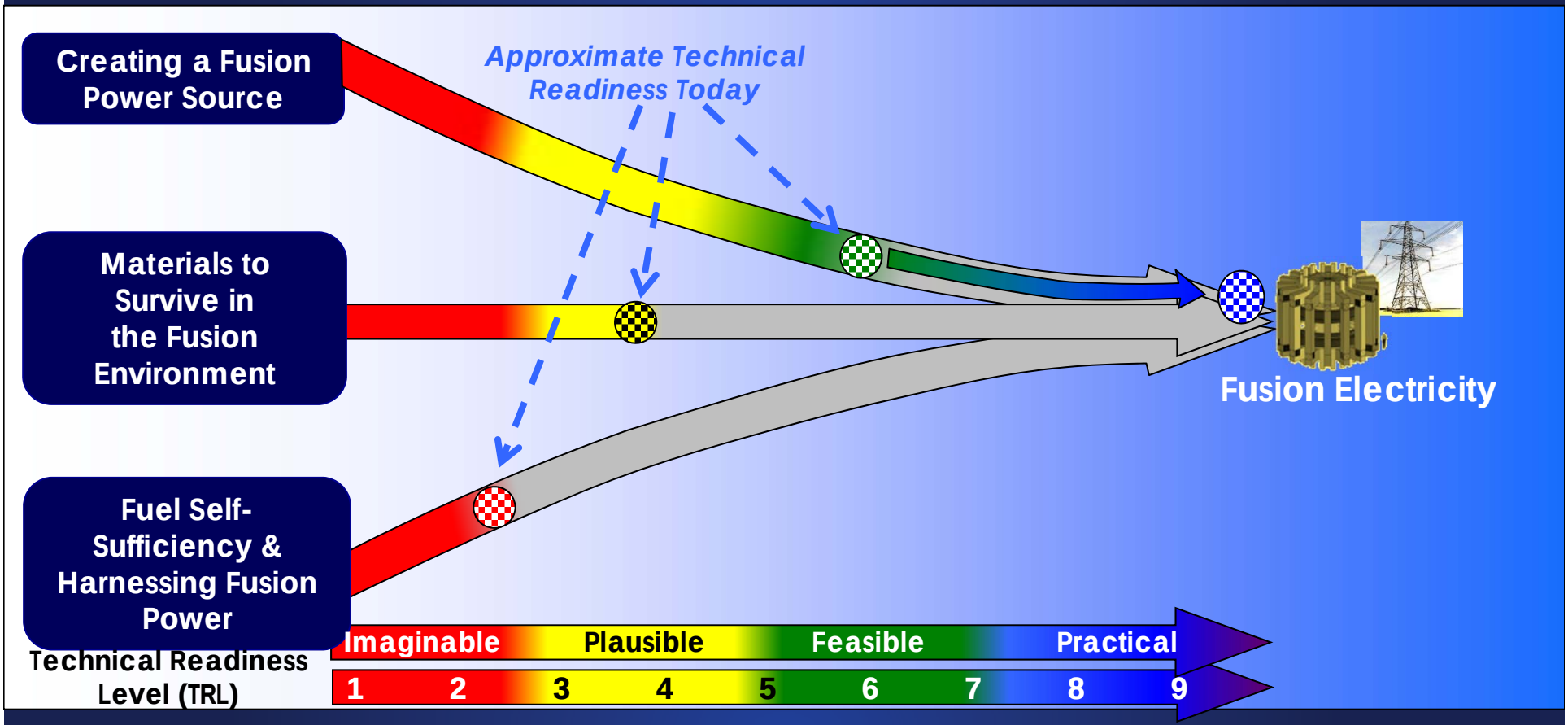
The Challenge of Fusion: Generating Electricity from Fusion Energy Requires Resolution of Three Scientific/Technological Challenges

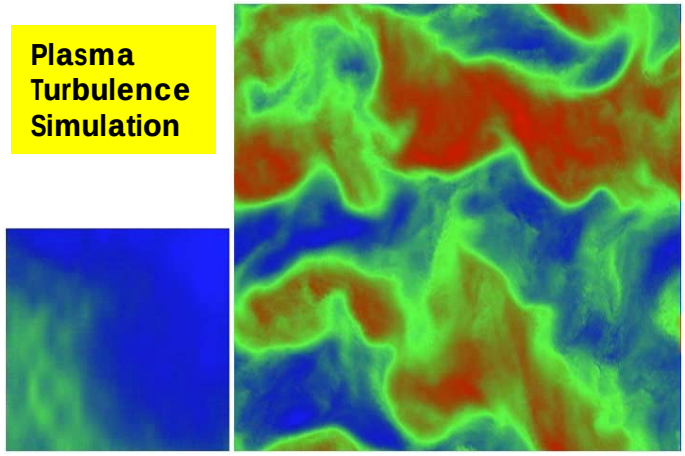


Producing a Fusion Power Source is Very Similar to Starting a Fire

- **Must get the wood (plasma) hot enough for long enough to "ignite" the system**
  - Fire: 2,000 ^{o}F
  - Plasma: 200,000,000 ^{o}F

- **But, … Self-generated turbulence is generated**
  - Gets more intense as more heat is generated by the fire/plasma

Plasma Turbulence Simulation



What Makes Burning Plasmas Unique?

- **"Burning plasma" occurs when self-generated heating (by fusion) exceeds applied heating**

- **System transitions from endothermic (absorbs heat) to exothermic (produces heat)**

Endothermic

Exothermic

- **Highly non-linear behavior can result**
  - Response of the system is not proportional to the input it receives
  - Superposition (i.e., simply adding up) of solutions doesn't work any more
  - Potential for highly chaotic behavior

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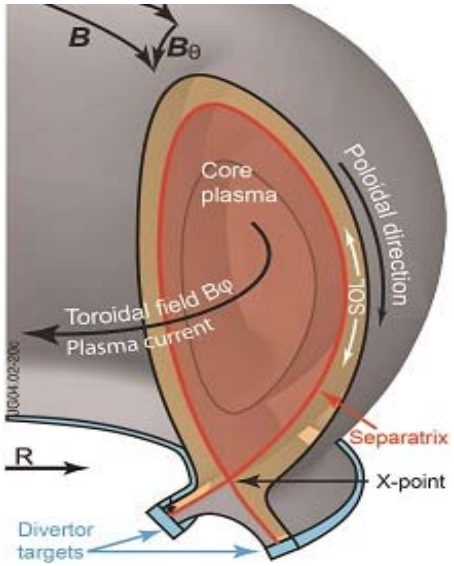
ITER will provide the first glimpse into this behavior

Endothermic

Exothermic

Handling the Power Flowing Out of the Plasma is Also a Serious Challenge

- **Best tokamak performance found when hot particles escaping main plasma are channeled to a separate region**
  - Region known as the divertor
- **Heat fluxes on material surface can exceed those of a rocket nozzle**
  - > 10 MW/m^2
- **Long time-scale operation (> 30 s) only possible with effective mitigation measures and excellent surface cooling**



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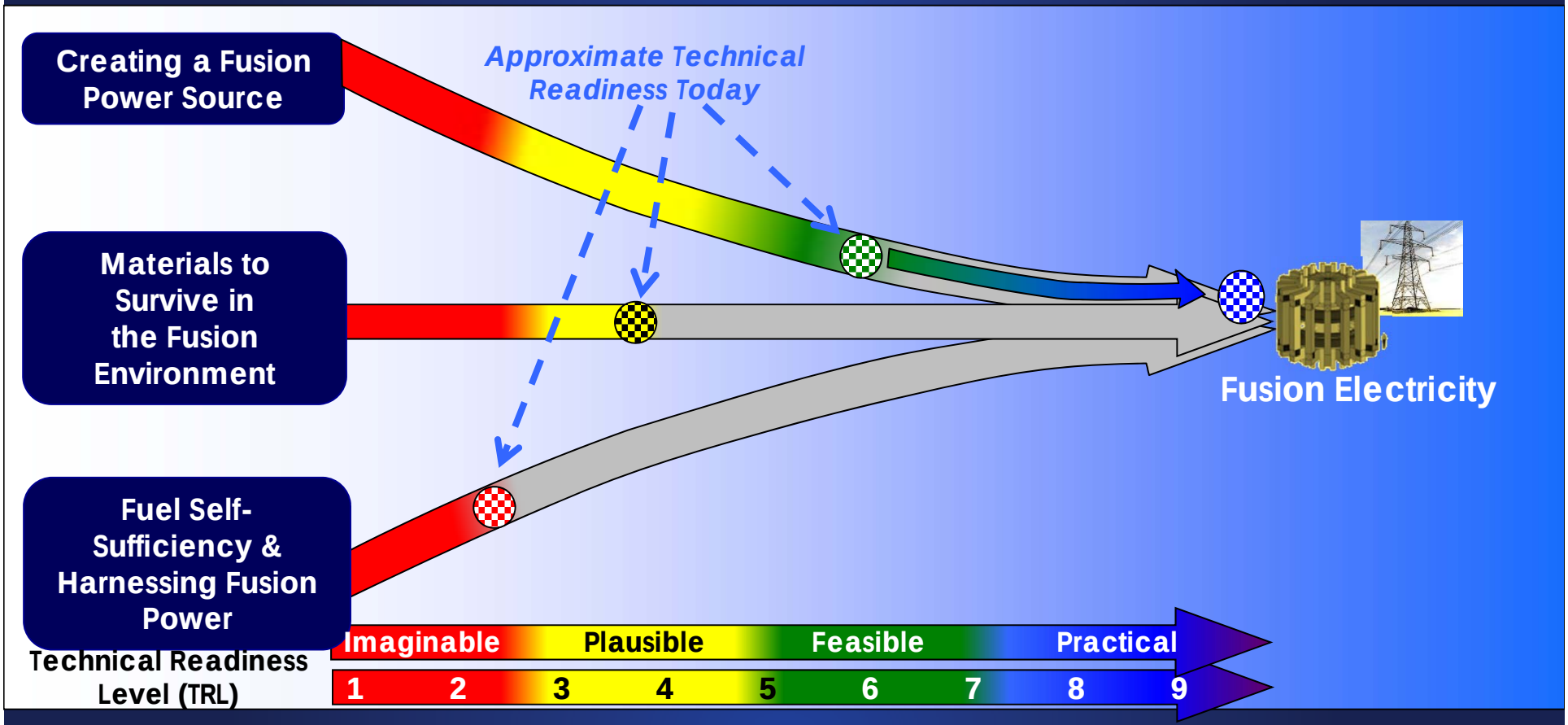
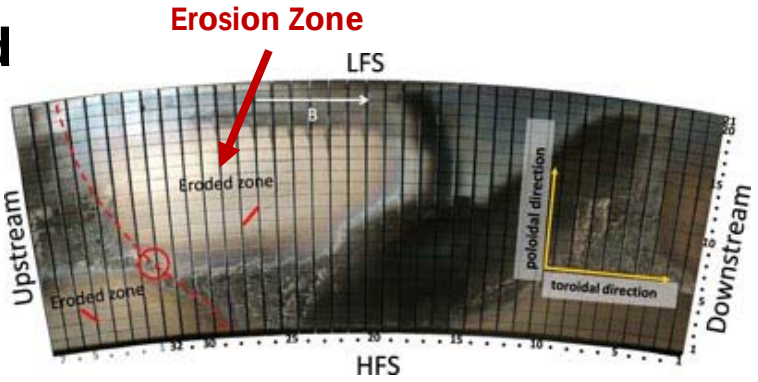
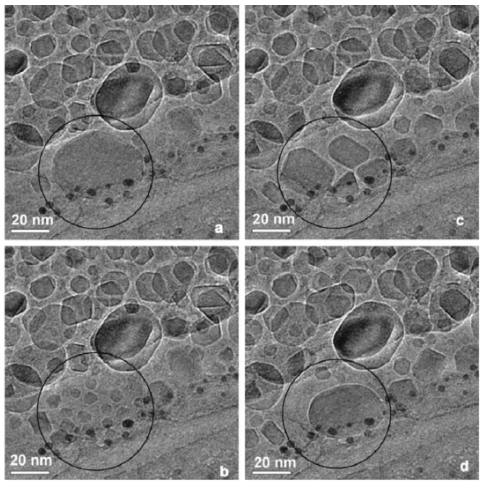


Material Survivability in Extreme Conditions is Also a Major Challenge

- **Materials must maintain their integrity and function while subject to:**
  - Very high heat fluxes (> 10 MW/m^2)
  - Bombardment by 14-MeV neutrons
- **Key issues include:**
  - Erosion: Rates must be maintained below a few millimeters / year
  - Transmutation: Material properties (e.g., thermal conductivity) can change radically
- **Great opportunity for materials by design**





Helium Bubble Formation In Aluminum

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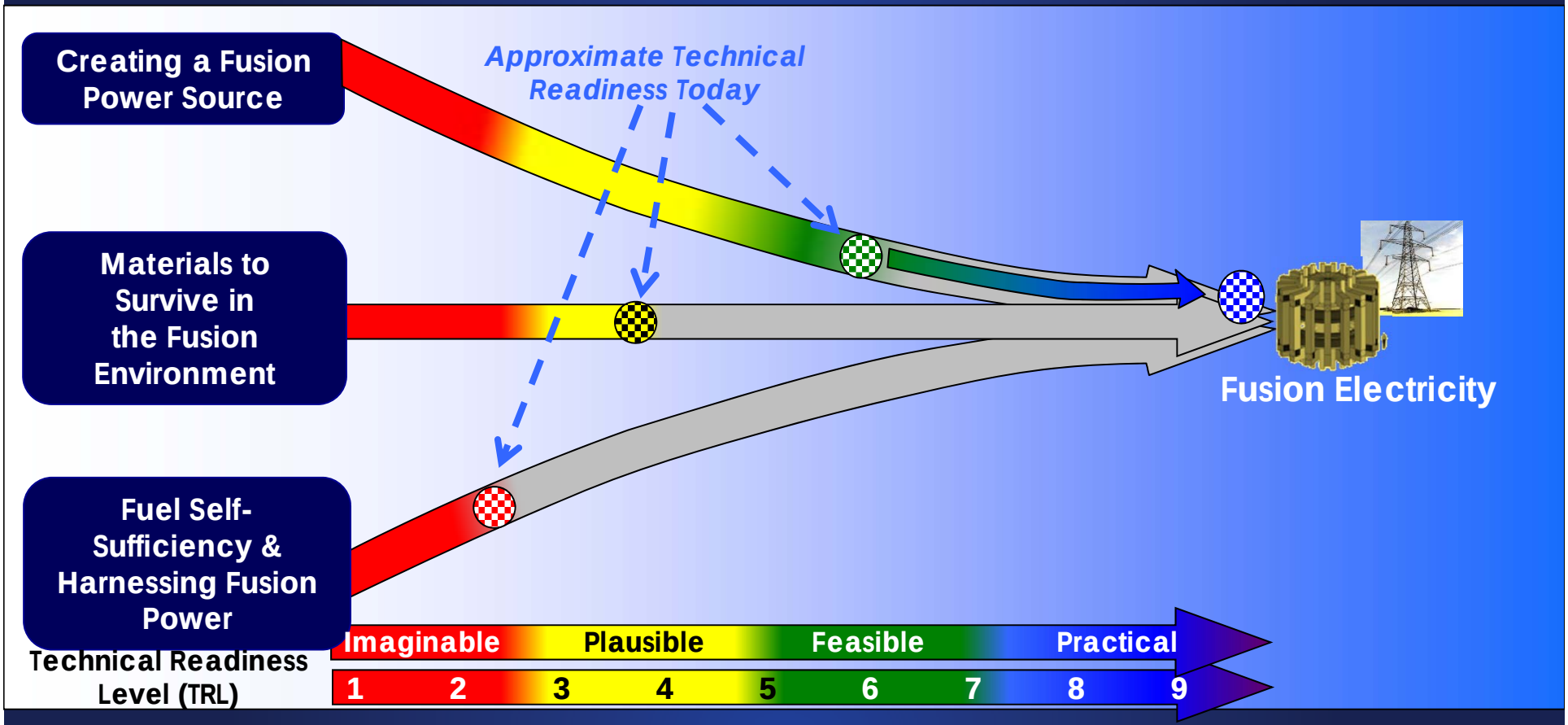
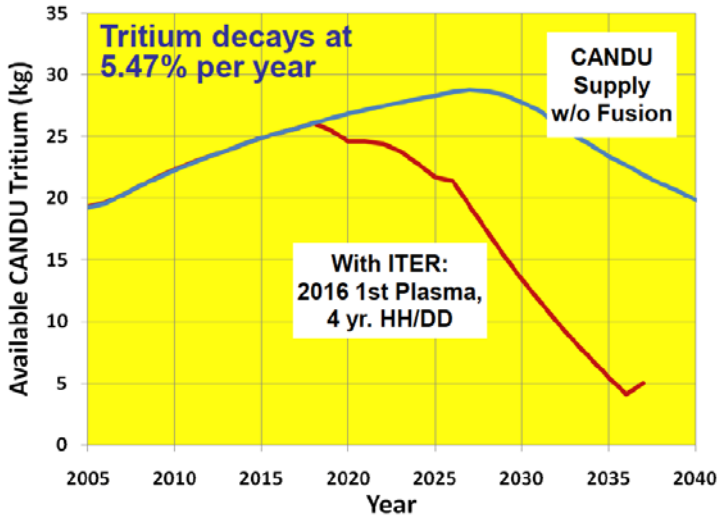
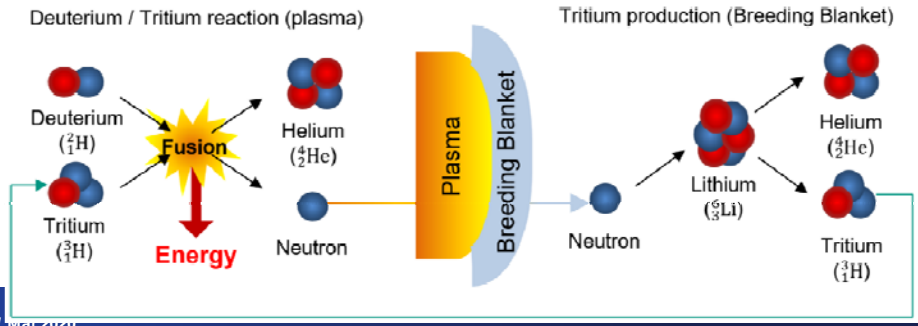


While the Raw Fuel Products are Readily Available, Tritium Will Need to be Produced to be Cost Effective

- **Tritium supply is very limited (and getting more so)**
  - 12 year half life
  - CANDU reactors scheduled for shutdown
  - ITER will use significant fraction of existing supplies
- **Solution → Produce tritium by having a "breed blanket" around fusion core**
  - Must "breed" more than is consumed
- **Basic process well established... but never demonstrated at rates needed for fusion**

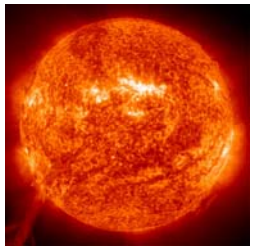


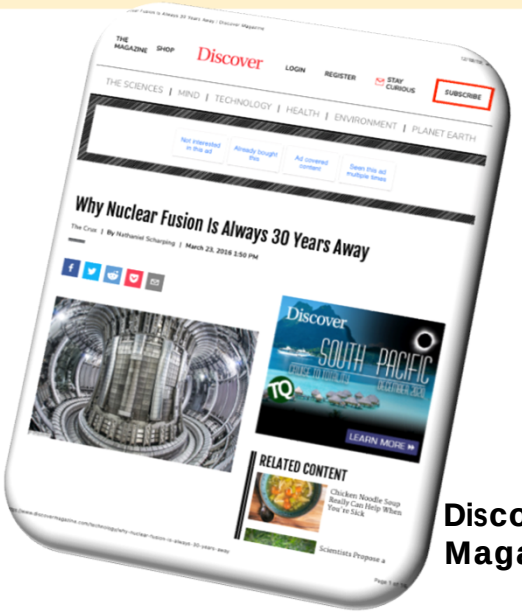


A Few Final Thoughts

- **Fusion energy is pretty close to the perfect energy source**
- **Fusion energy is possible**
- **Fusion energy is challenging**
- **Fusion energy is needed…**

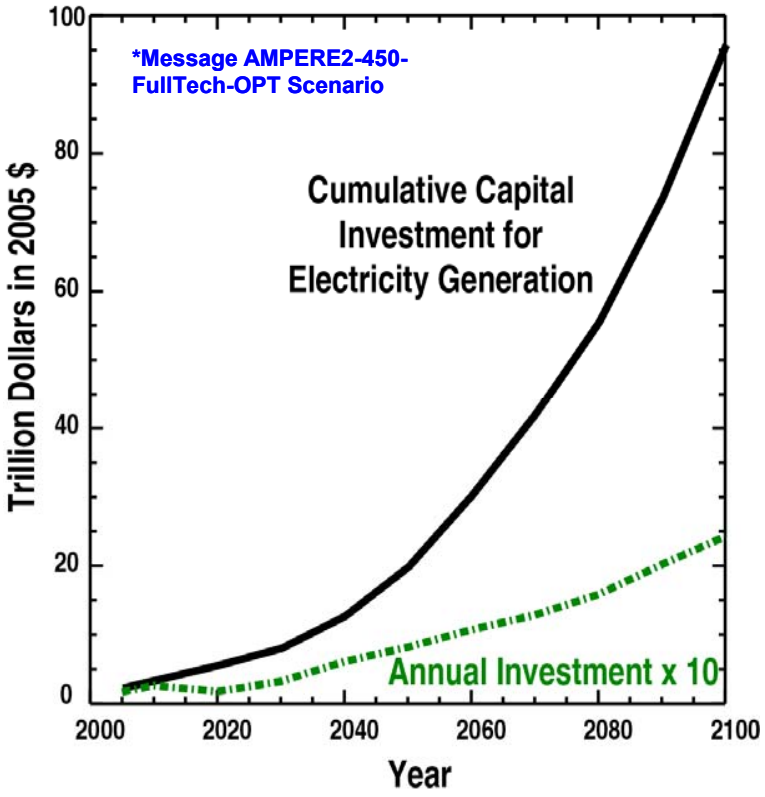
"I would like nuclear fusion to become a practical power source. It would provide an inexhaustible supply of energy, without pollution or global warming." Stephen Hawking





Discovery Magazine 2016

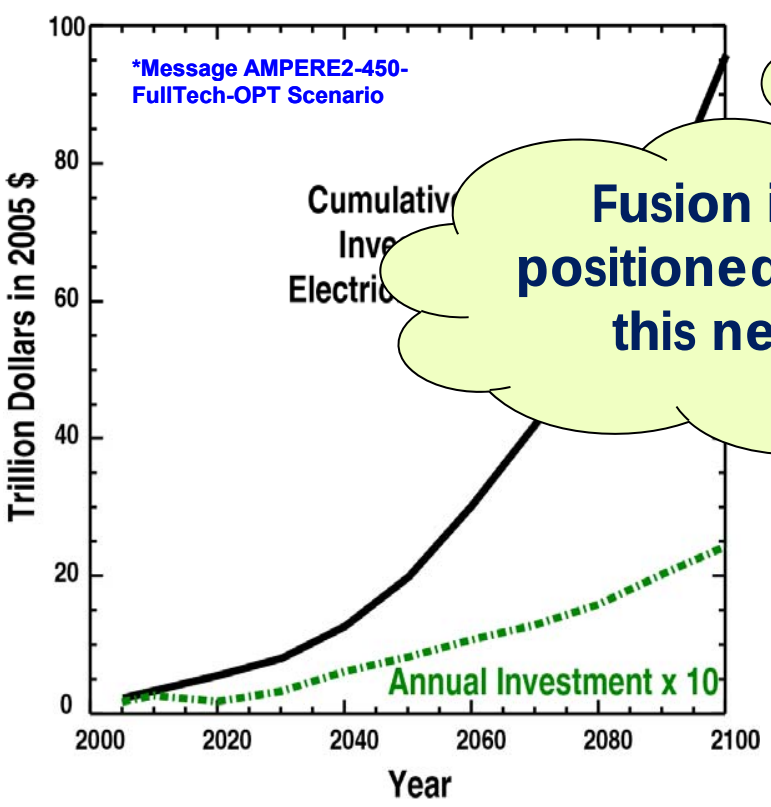
Future US Economic Security Hinges on Our Ability to Capitalize on a Coming Tsunami in Energy Investment → $2.5 T Annually by 2100



- **For reference: (2015 values)**
  - GDP of US : $18 T
  - GDP of China: $11T
  - GDP of UK: $2.8 T

- **Growth driven by:**
  - Population growth
  - Improving standard of living in Africa and SE Asia
  - Electrification of the transportation sector

Future US Economic Security Hinges on Our Ability to Capitalize on a Coming Tsunami in Energy Investment → $2.5 T Annually by 2100



Fusion is well positioned to meet this need…

- **For reference: (2015 values)**
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  - K: $2.8 T

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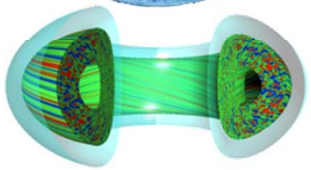
Facility to Enhance Attractiveness of Pathway is Key to Accelerating Path to Pilot Plant/FNSF

Develop Foundation for Tokamak Approach to Fusion

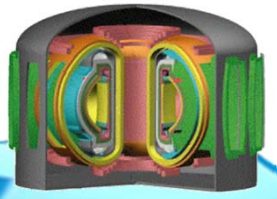
Experiments Worldwide



Theory and Computation

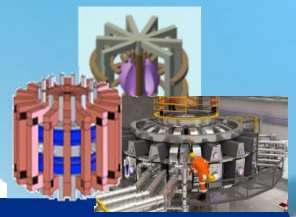
Secure Benefit of ITER Construction

...But timely, concerted effort is needed!!!



Cost-attractive Pilot Plant/FNSF

New fusion facilities (incl. materials, magnets, blankets)



Enhance Attractiveness, Timeliness of Pathway and/or End Product

Facility to Enhance Attractiveness of Pathway is Key to Accelerating Path to Pilot Plant/FNSF

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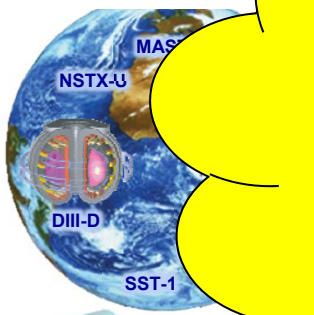
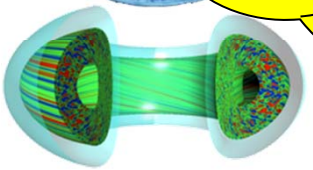
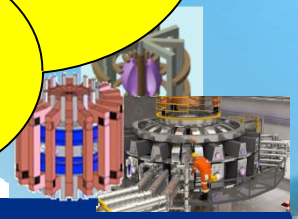




Theory and Computation

Events have conspired to bring us to this point of potential grave threat and immense opportunity …

History will judge us by our response



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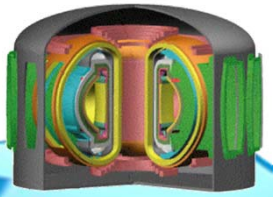

Cost-attractive Pilot Plant/FNSF