Oak Ridge National Laboratory

Integrating Physics and Engineering for Fusion Reactor Design, Assessment, and Optimization

Cami Collins

copy of this talk

Michigan Institute for Plasma Science and Engineering
Nov 15 2023

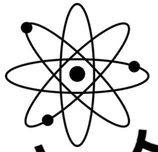
U.S. DEPARTMENT OF ENERGY

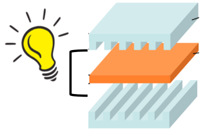
Quick introduction: my path in fusion

5th Grade	Undergrad	Grad	Postdoc	Scientist!	Scientist +
1995	2003-07	2007-13	2014-16	2016	2020

Montana State University · University of Wisconsin–Madison · UC Irvine (University of California, Irvine) · General Atomics · Oak Ridge National Laboratory

Fusion=awesome



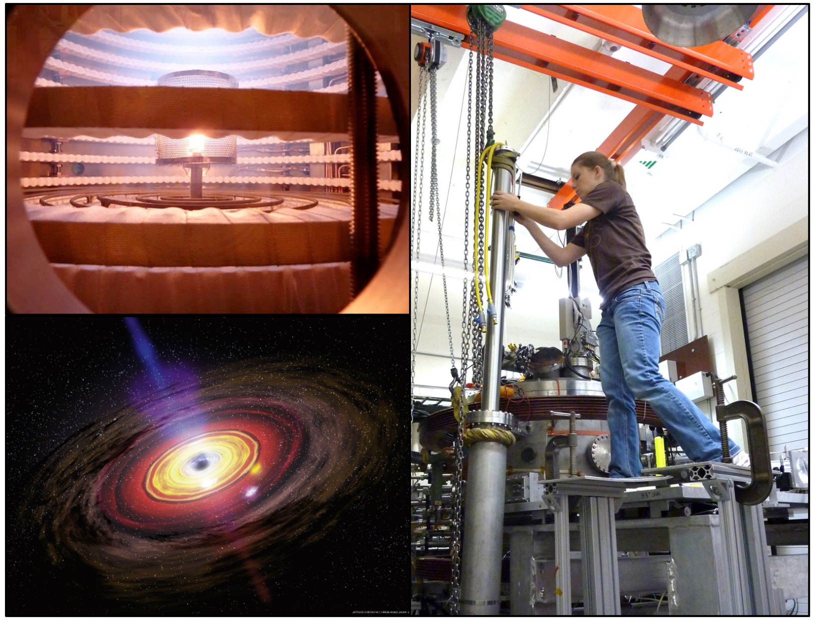


Solid Oxide Fuel Cells (materials)

Solar Physics

Fusion

Nat. Und. Fellowship



Laboratory Plasma Astrophysics

Fusion Energy Fellowship

Fusion=hard

I want to help design a fusion pilot plant.

I’m excited about the (recent) history of fusion

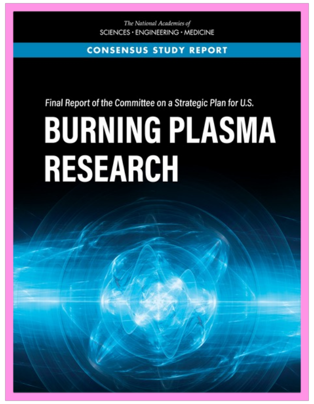
Fusion community comes together – historic success

Strategic Workshops

Community Planning Workshops

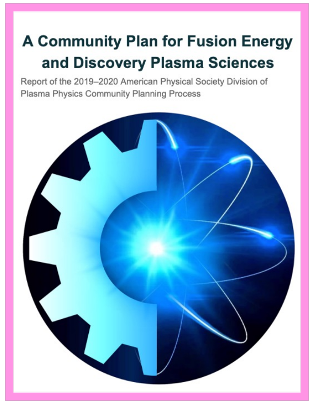
2019 2020 2021 2022

National Academies
Dec 2018



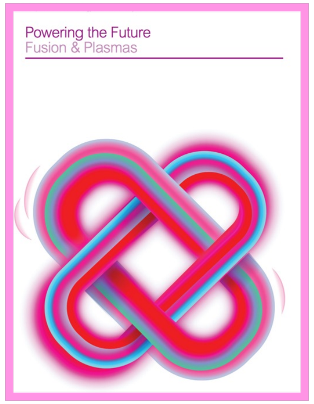
We’ve advanced - let’s make a fusion pilot plant by the 2040’s!

APS-DPP-CPP
Mar 2020



Here’s what we need to do!

FESAC
Dec 2020



Hey DOE: do what they said! (but here’s how much it costs)

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Strategic Workshops ←

Community Planning Workshops ↔

2019 | 2020 | 2021 | 2022

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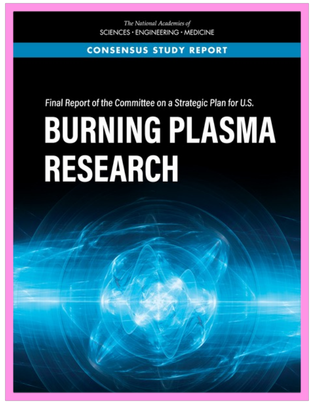

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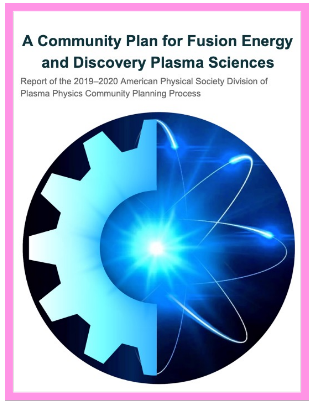

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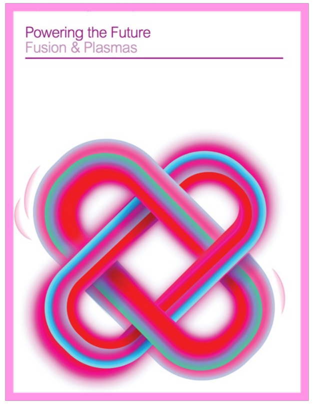

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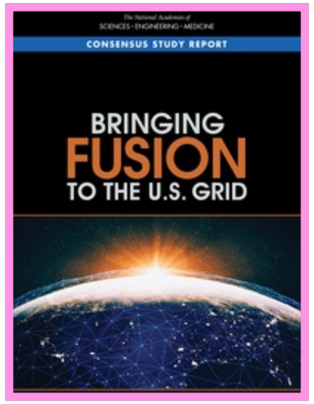
National Academies
Feb 2021



Get going! We need design by 2028, electricity by 2035!

Milestone
Program
Sept 2022

DEPARTMENT OF ENERGY (DOE)
OFFICE OF SCIENCE (SC)
FUSION ENERGY SCIENCES (FES)

OK private industry, prove it.

ITER Plan
Oct 2022

U.S. ITER
RESEARCH
PROGRAM
www.iterresearch.us

Use ITER. There's a lot to learn.

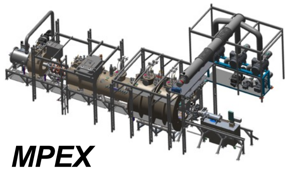
I joined ORNL because of its potential to execute the community plan

Our vision: Fusion energy will be an electricity source for *this generation*.

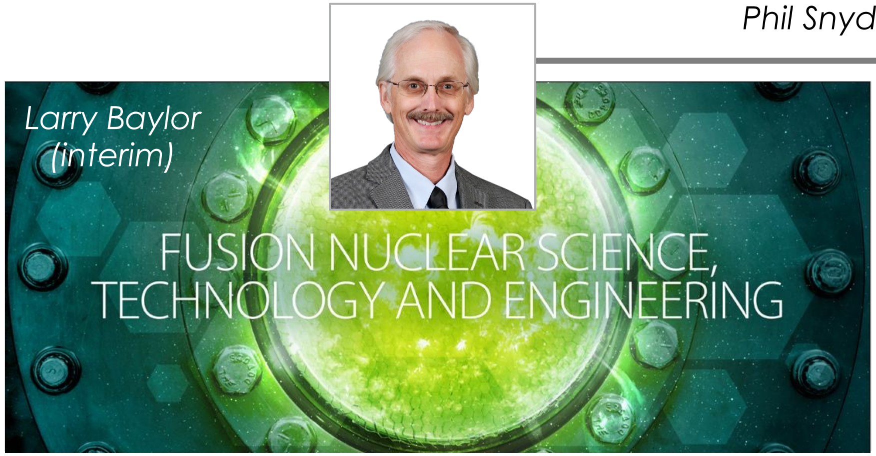
Integrated Fusion Systems — ORNL FUSION ENERGY DIVISION — ***Public and Private Partnerships***

Phil Snyder (interim)

Plasma Material Interactions Science



MPEX



US iter

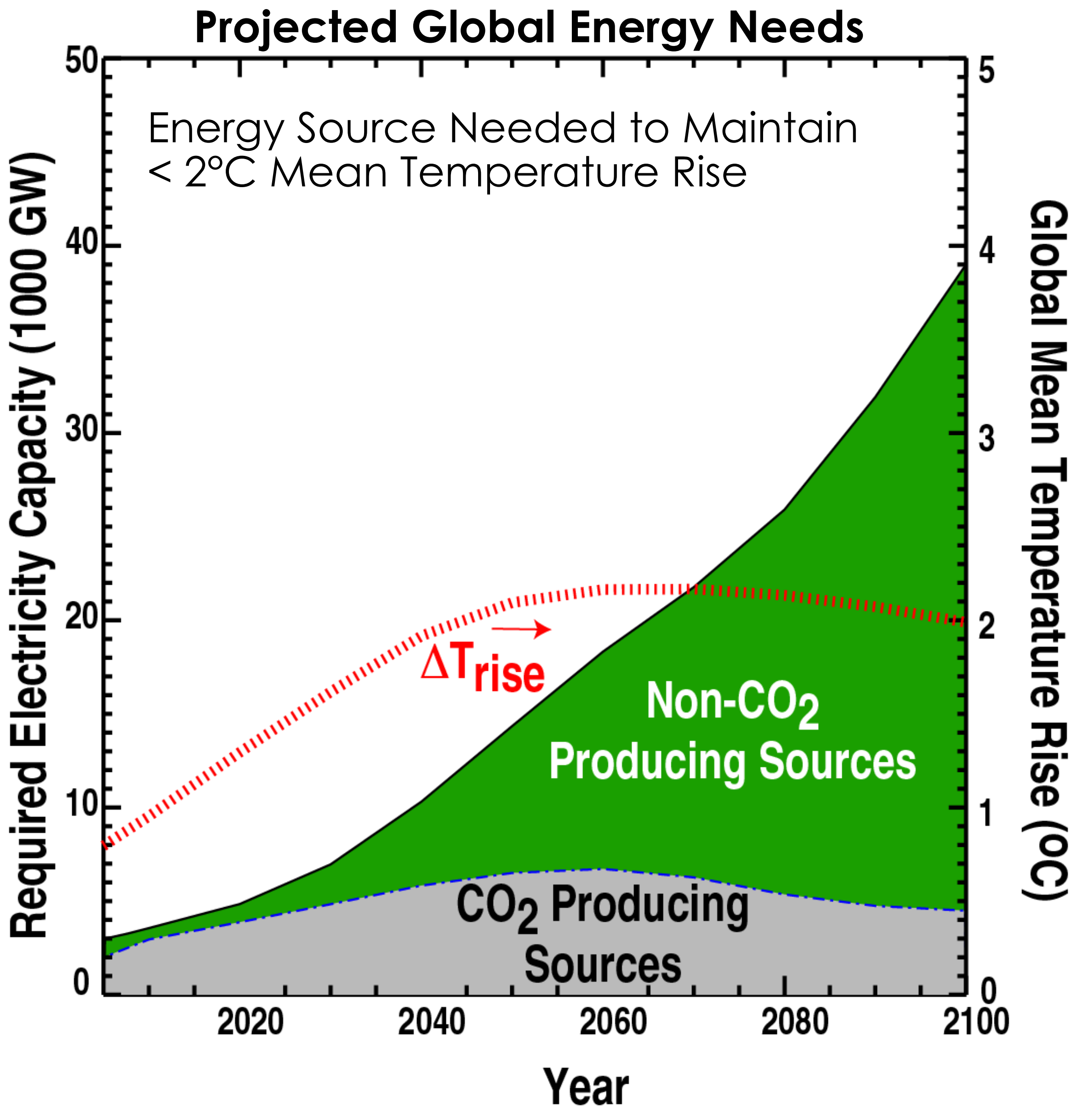
Blanket & Fuel Cycle	Fusion Technology	Fusion Engineering	Remote Systems	Power Exhaust & Particle Control	Advanced Tokamak Physics	Plasma Theory & Modeling	Diagnostics & Controls
Larry Baylor	*Robert Duckworth*	*Arnold Lumsdaine*	*Venu Varma*	*Zeke Unterberg*	*Morgan Shafer*	*Gary Staebler*	*Ted Biewer*

Materials Science **Advanced Manufacturing** **Fission** **High Performance Computing**

Outline

- Motivation for magnetic fusion energy
- Challenges and frontiers in developing fusion energy
  - Burning plasma and fast-ion physics (focusing on tokamak)
  - Handling reactor conditions
  - Capturing the energy
- Progress in enabling more rapid fusion pilot plant design

The Future of Our Civilization Depends on Energy



Source: IPCC AMPERE Project, AMPERE-450-FullTech-OPT Scenario

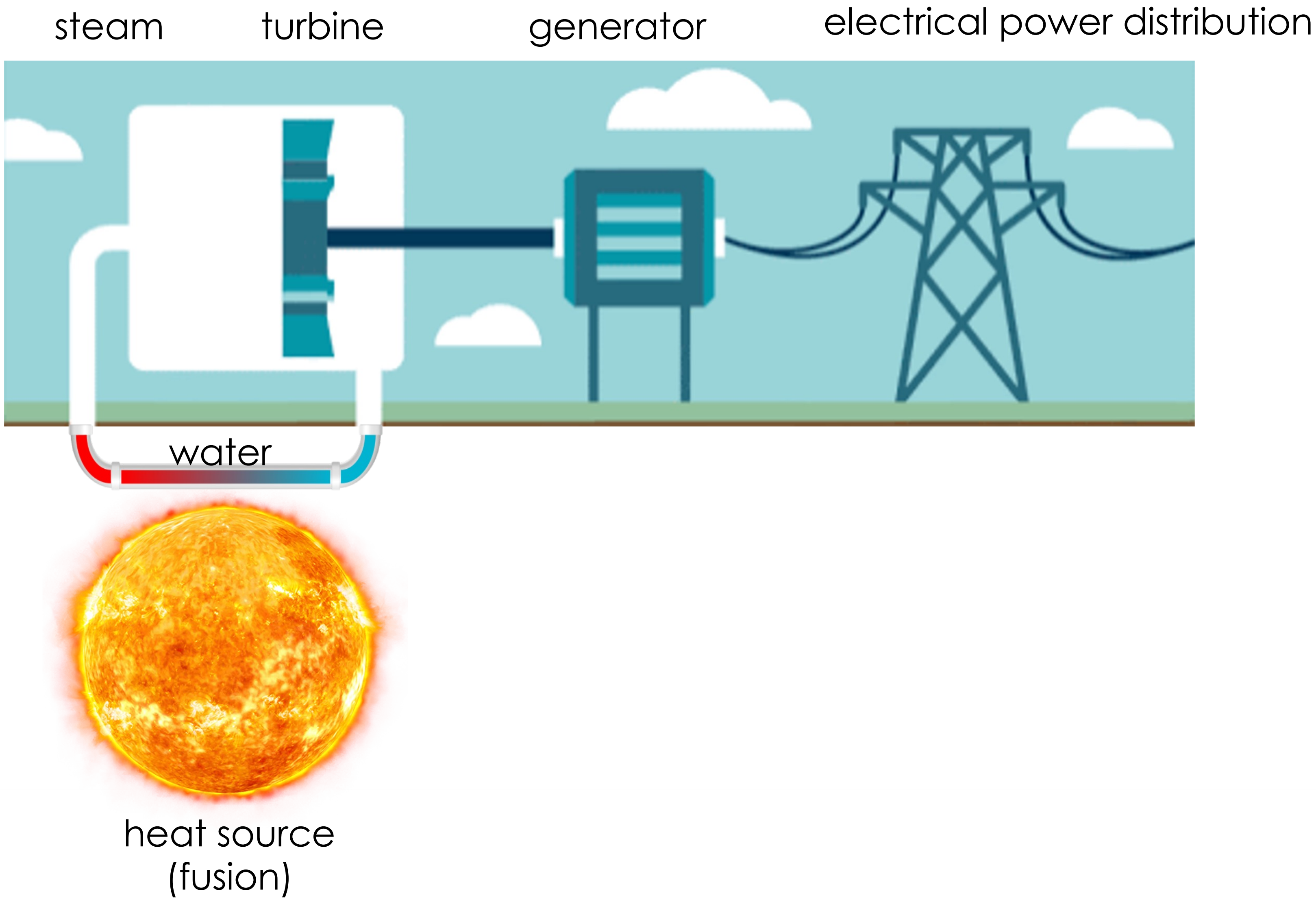
- Projected need for ~ 25,000 GW from non-CO_2 producing sources

25,000 1 GW-e plants !!!

- By 2050, annual global energy investment would need to reach $0.66 T ($23 T cumulative)
  - GDP (2018): US: $21T, China: $14T, UK: $2.9T
  - Global cell phone market: $0.55 T

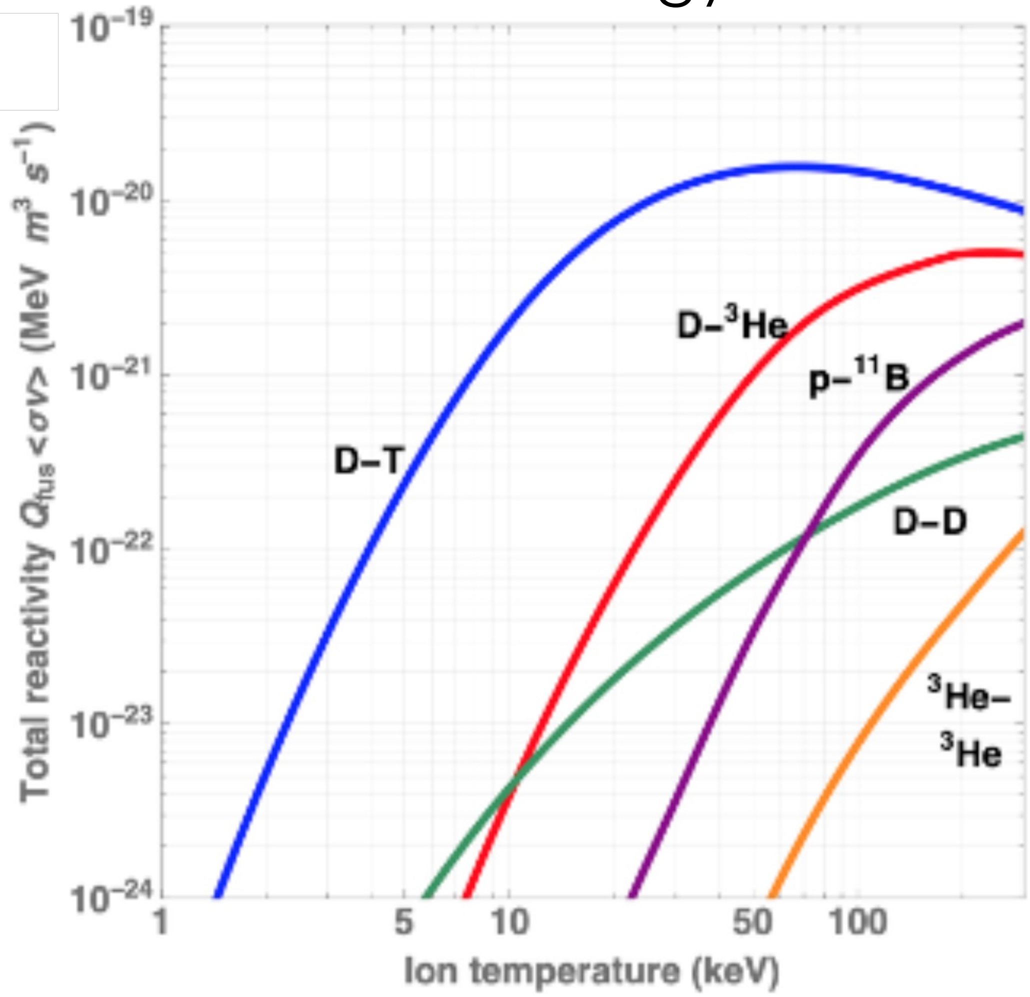
Source: IRENA, Global energy transformation, 2019

Awesome! How Do We Make A Fusion Power Plant?



Deuterium-Tritium Fusion is the "Easiest"

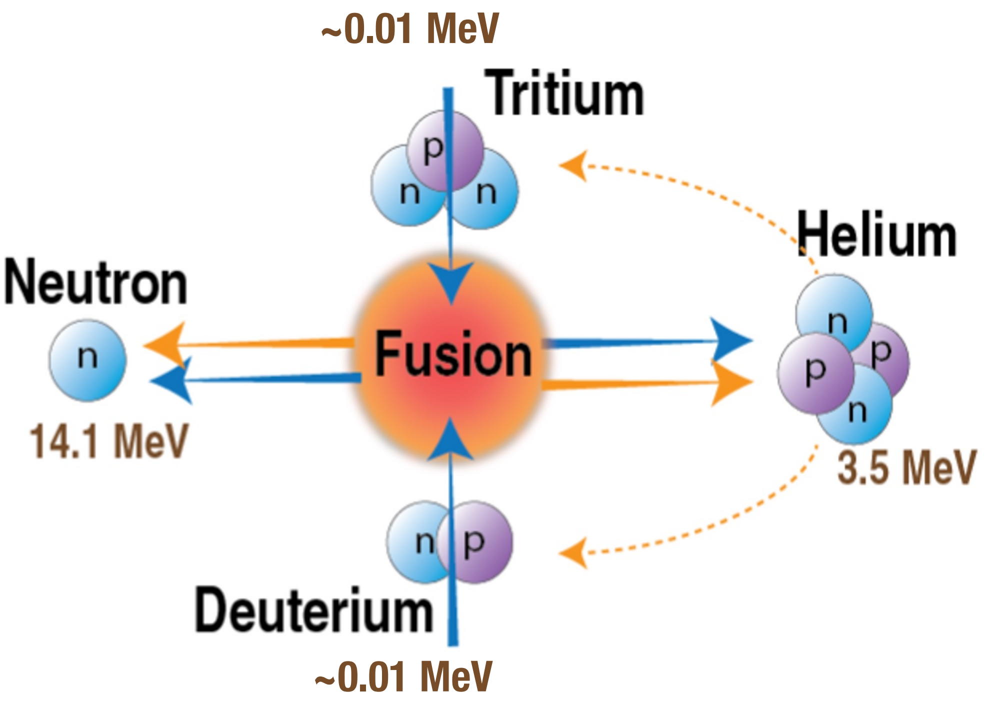
Reaction cross section times total energy released



- Fuel cycles like D-D, D-^{3}He, p-^{11}B
  - Produce less neutrons, reduces the requirement for neutron-tolerant materials in a fusion pilot plant
  - Removes need for tritium breeding
  - BUT require higher temperatures than D-T, require novel surface energy removal technology and configurations

DT Fusion Fundamentals

80% of the energy collected to generate electricity



alpha particle heating:

20% of the energy stays to sustain the reaction

To produce 1000 megawatts electricity for 1 day (enough for a major city)

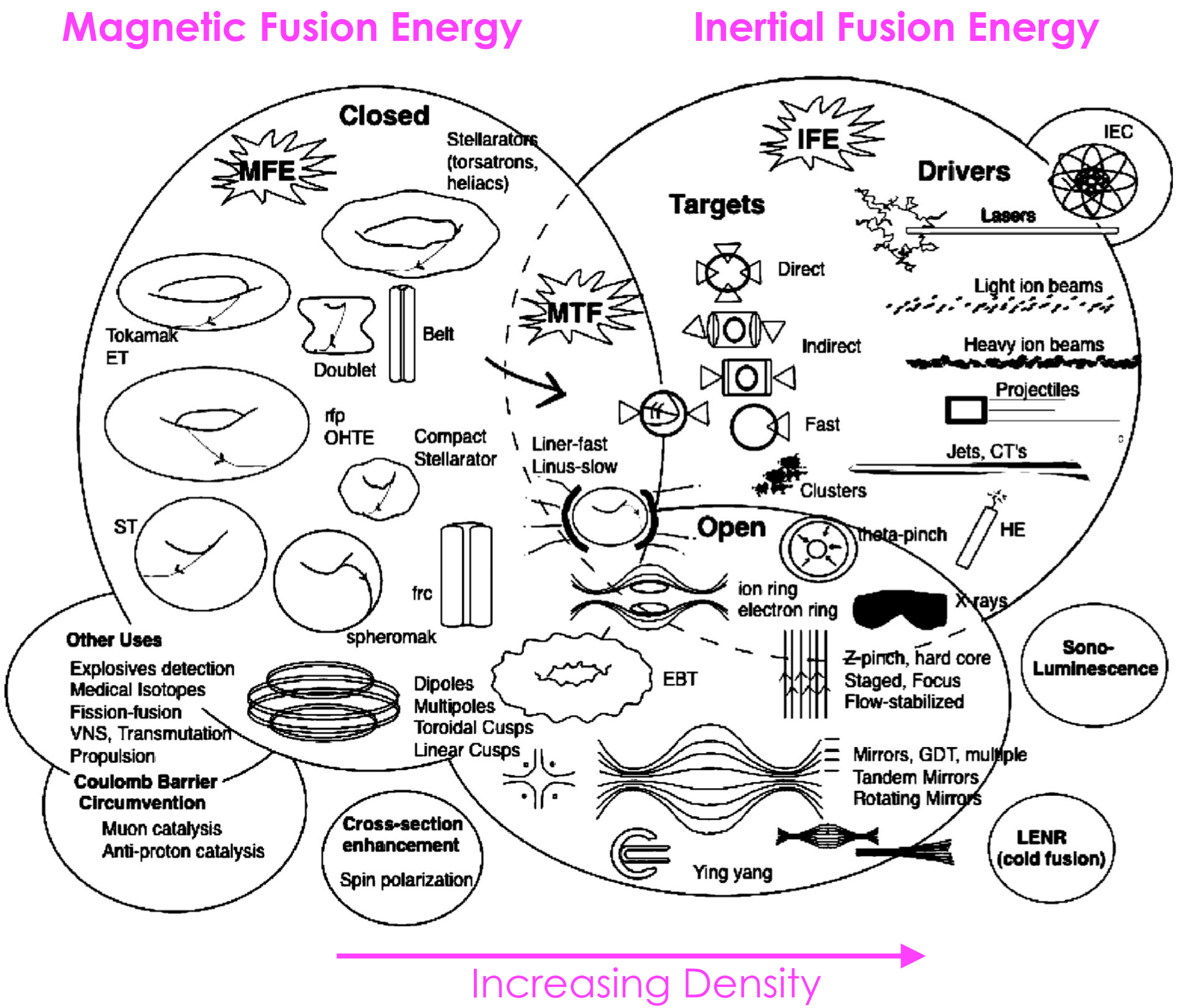
1.0 Lb D_2
1.5 Lb T_2

3
water bottles

2.0 Lb helium

400
balloons

There Are a Lot of Fusion Concepts Out There



S. Woodruff, Journal of Fusion Energy, 23 (2004) 27-40

The Triple Product is a Fundamental Figure of Merit

- Self-sustaining fusion reaction requires high fusion gain

$$Q = \frac{P_{fusion}}{P_{heat}}$$

- Triple product (Lawson criterion): energy released in fusion products must exceed the sum of the energy applied to heat

$$nT\tau_E > 2\text{x}10^{21}\ \text{m}^{-3}\text{-keV-s}$$ (for Q=10)

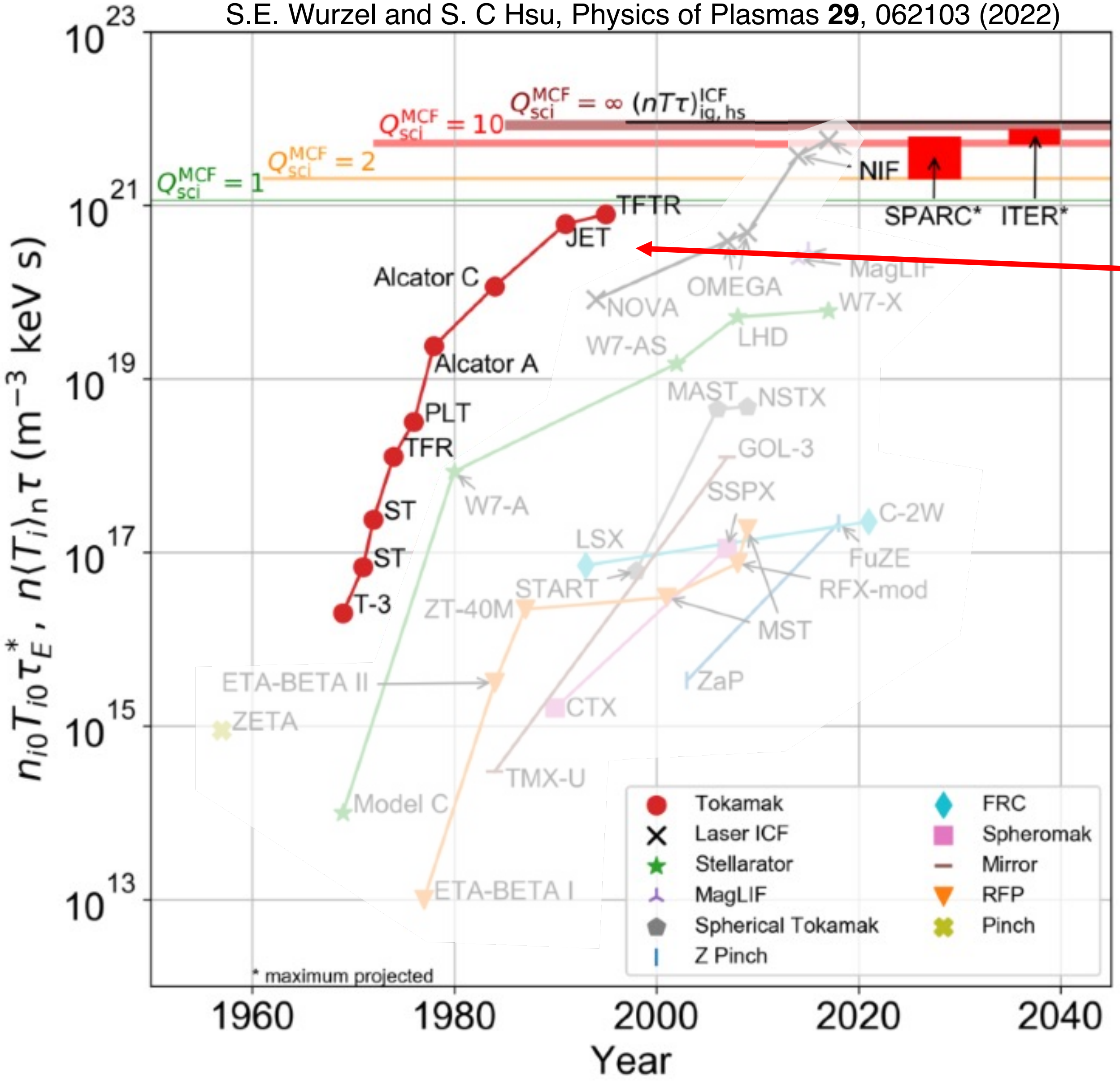
Density
(enough particles)
n~2-3x10^{20} ions/m^3

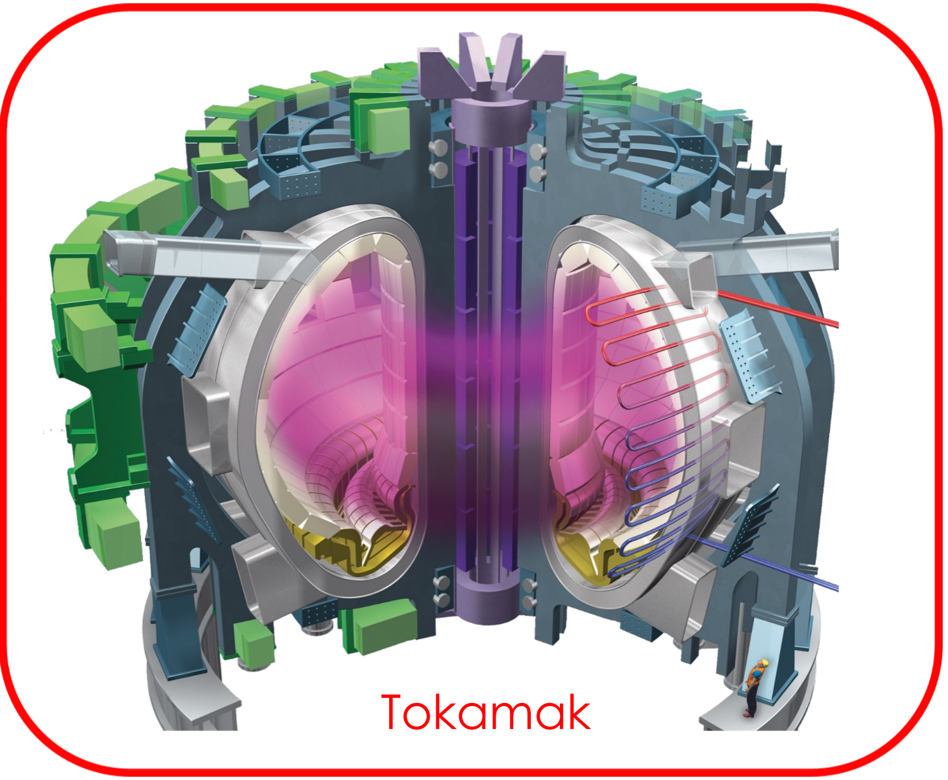
Temperature
(enough energy)
T~100-200 million K

Confinement
(enough time to collide)
τ_E ~1-2 seconds

Progress Toward Energy Gain

S.E. Wurzel and S. C Hsu, Physics of Plasmas **29**, 062103 (2022)





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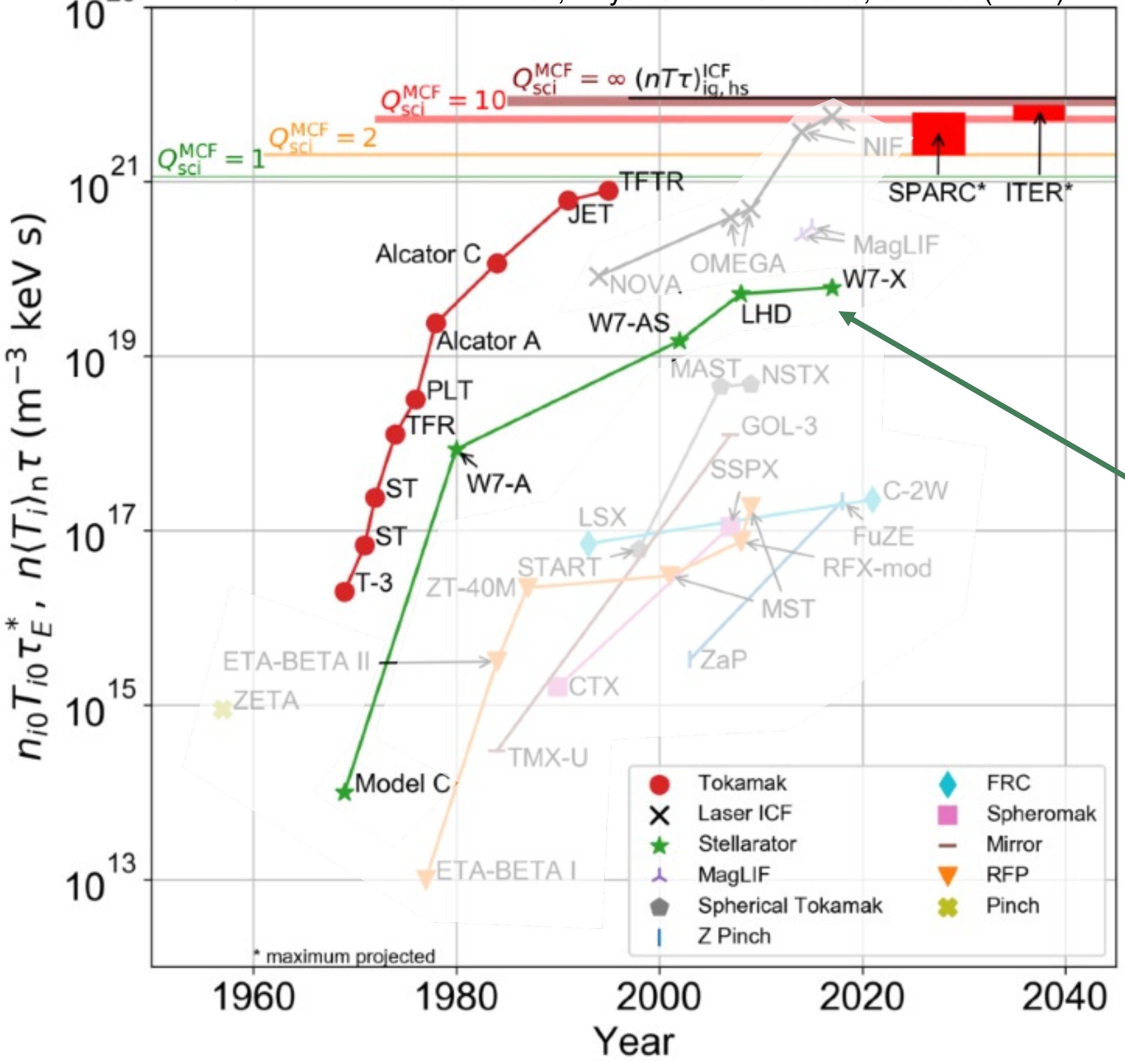
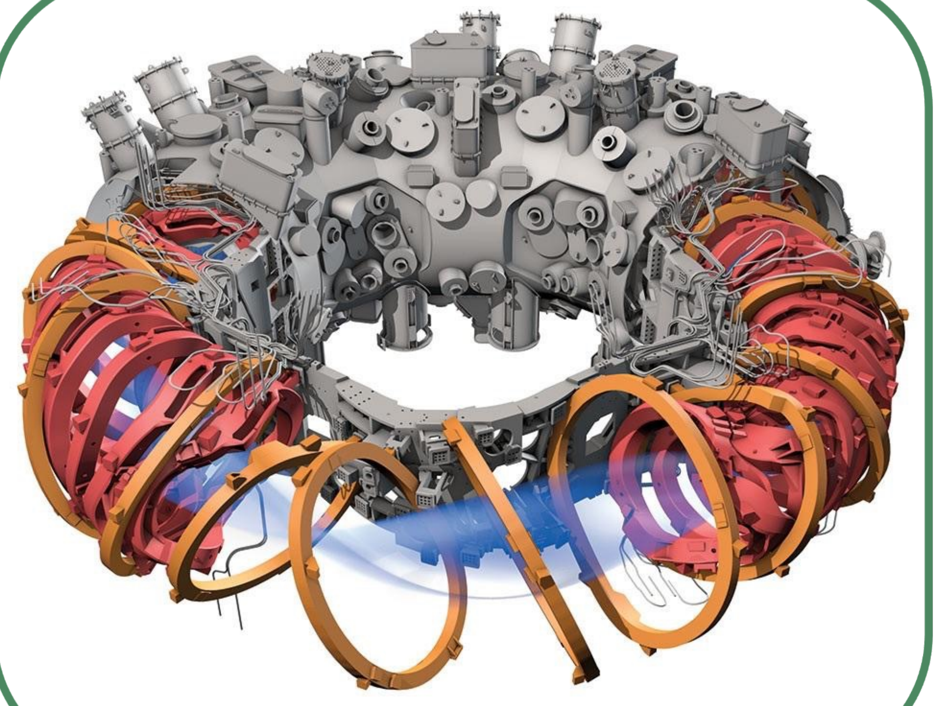
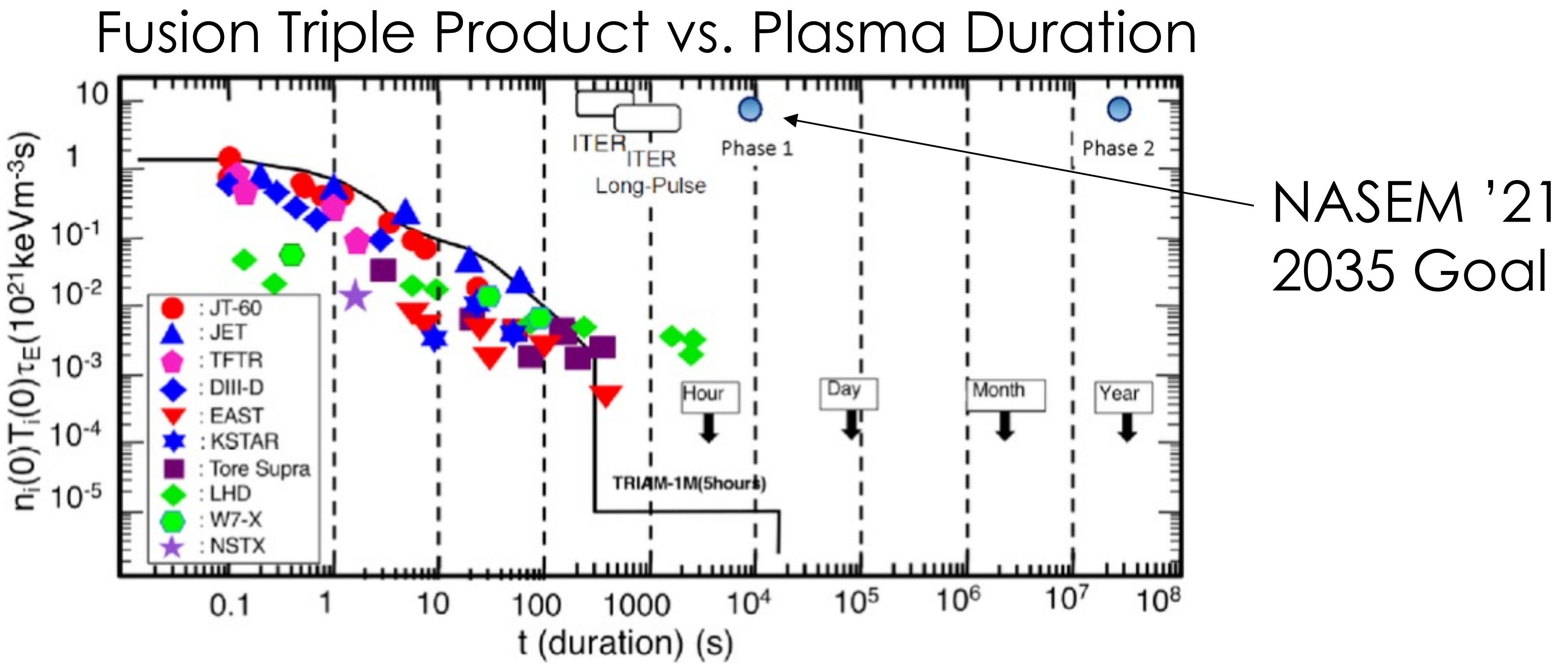




Stellarator

Making Electricity Is More Than Just Triple Product (or Gain)



- **Significant progress is needed to demonstrate high gain AND long-duration (or high rep rate) to be relevant for cost-effective, uninterrupted power production**
  - NASEM '21 (informed by utility co.)

- **Phase 1**: ≳50 MWe peak electricity generation for ≥3 hours with Qe > 1, closed fuel cycle
- **Phase 2**: Demonstrate heat removal, material erosion, and tritium loss is managed for ~year
- **Phase 3**: Fully define lifetime, availability, and manufactured components of commercial plants

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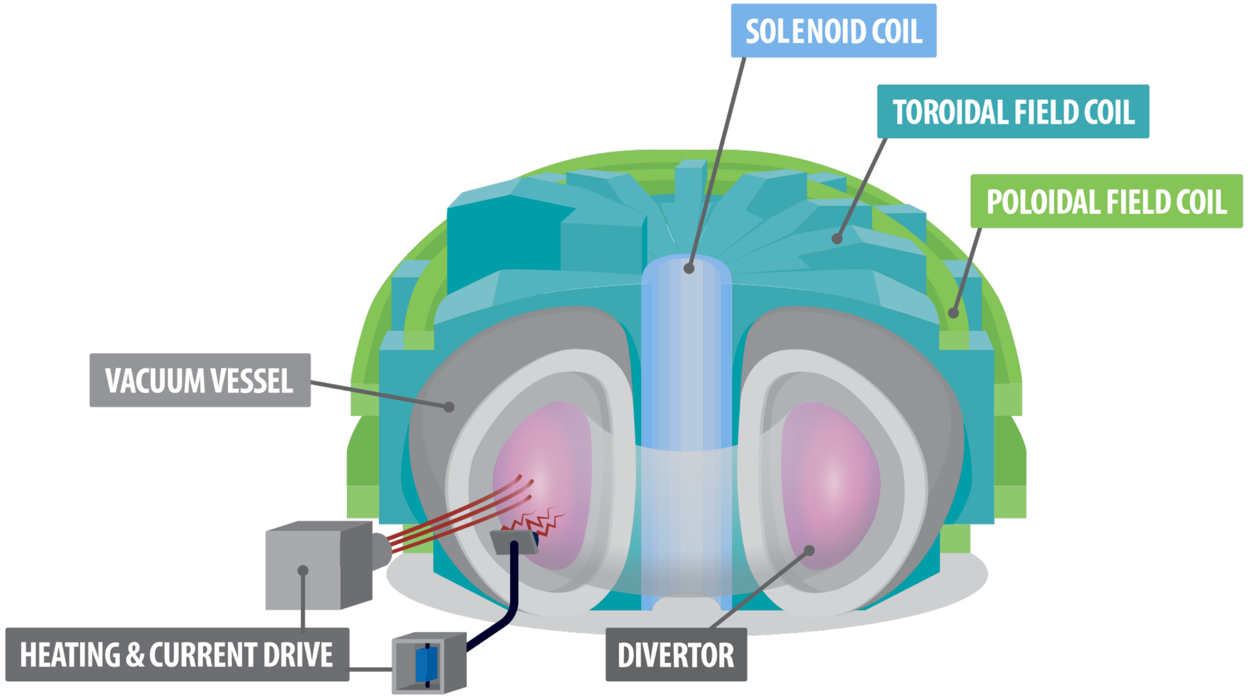
Generating Electricity from Fusion Energy Requires Meeting Three Scientific/Technological Challenges



<u>Control, sustain, and predict</u>
a high temperature "burning" plasma to produce neutrons/heat

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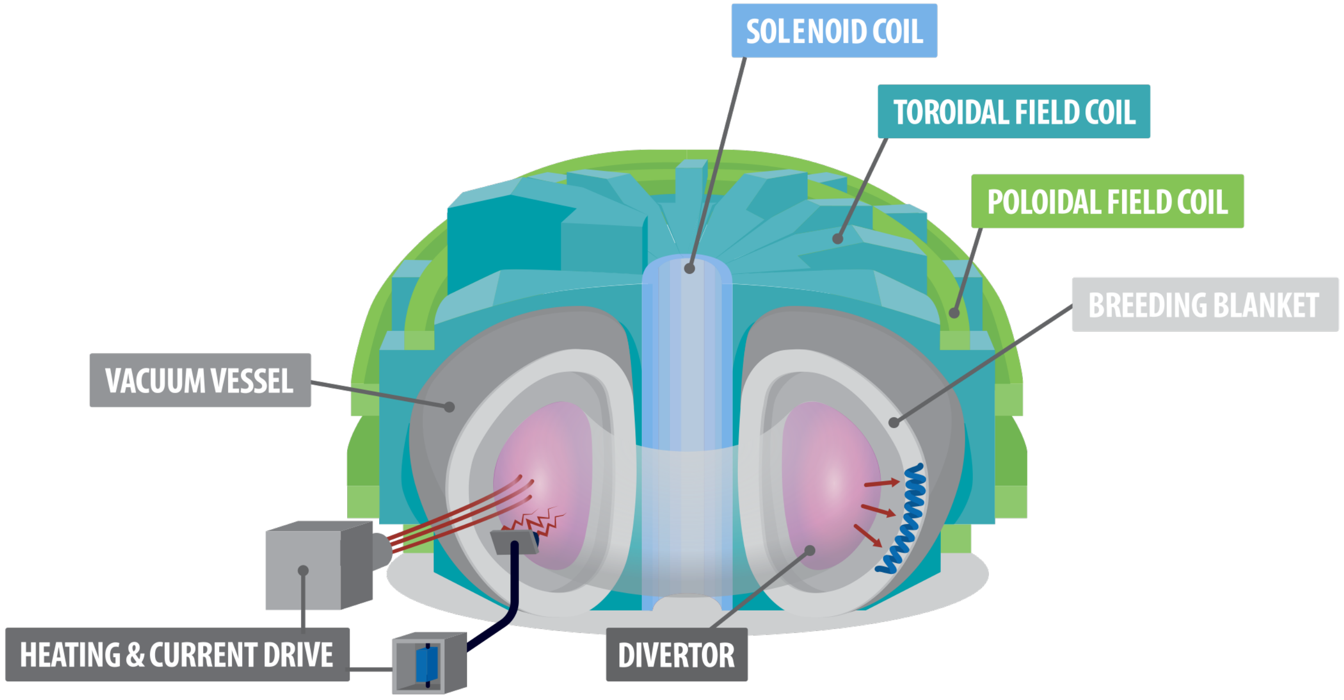
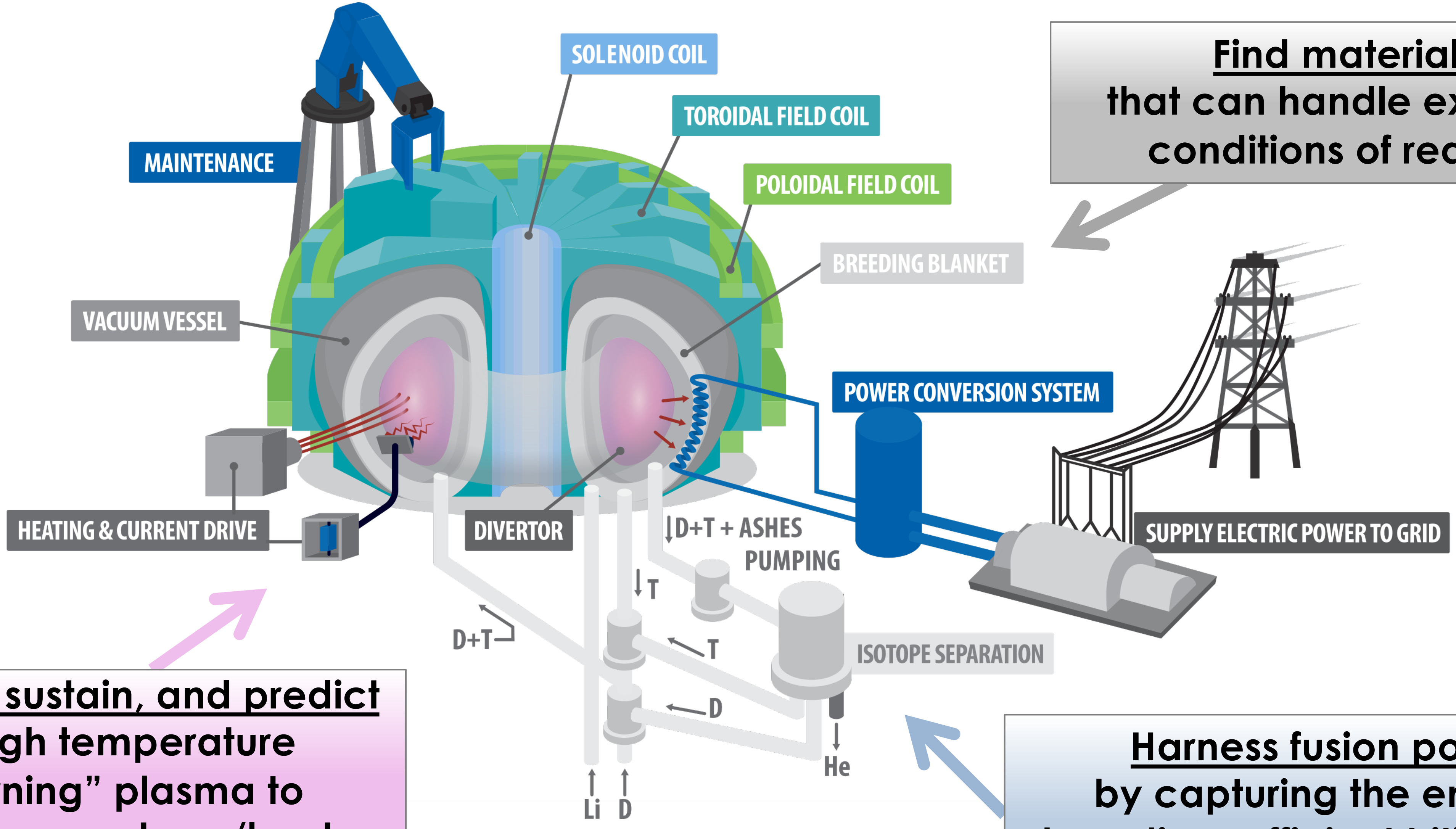


<u>Find materials</u>
that can handle extreme conditions of reactor

<u>Control, sustain, and predict</u>
a high temperature "burning" plasma to produce neutrons/heat

Generating Electricity from Fusion Energy Requires Meeting Three Scientific/Technological Challenges

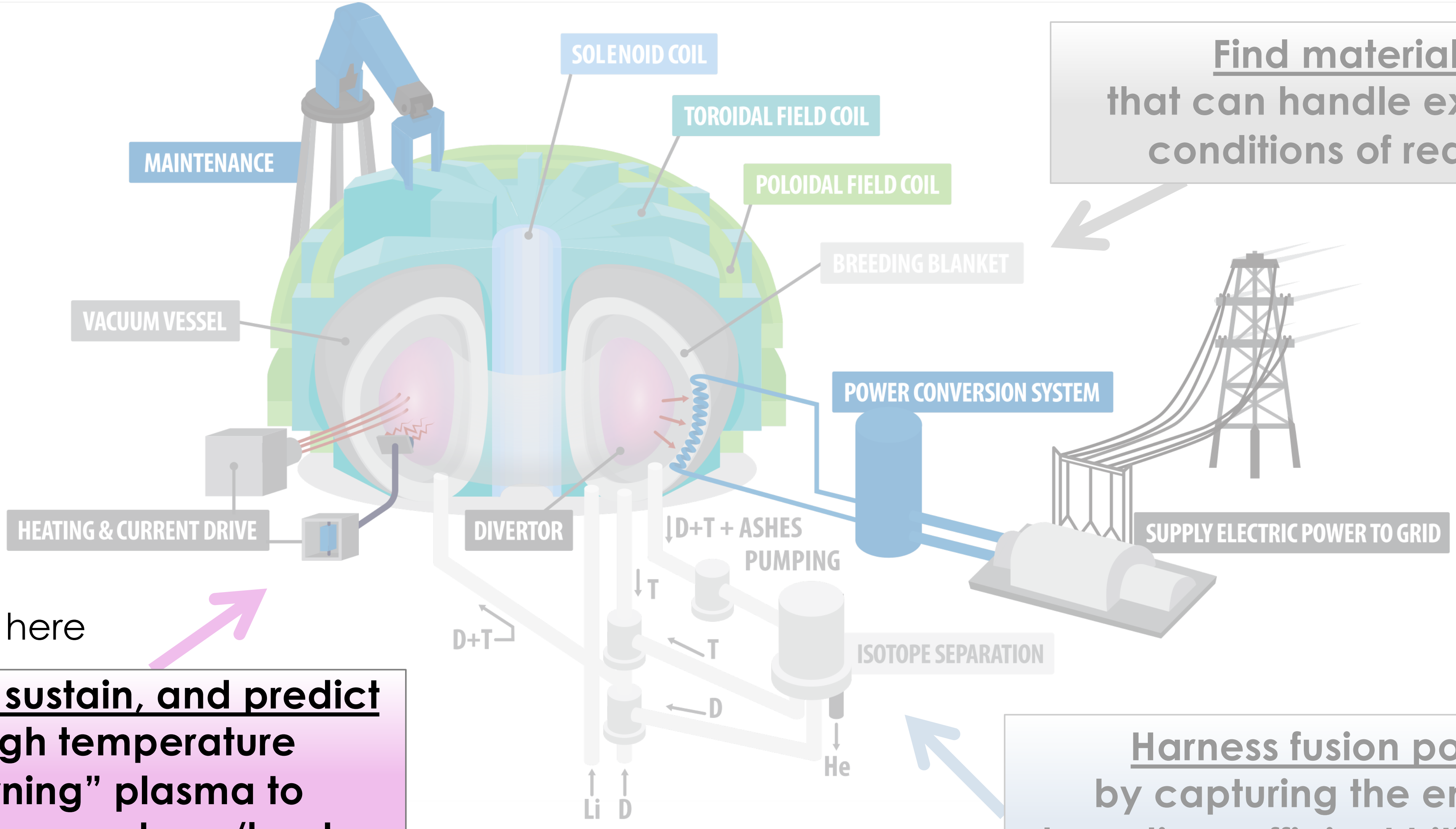


Find materials
that can handle extreme conditions of reactor

Control, sustain, and predict
a high temperature "burning" plasma to produce neutrons/heat

Harness fusion power
by capturing the energy, breeding sufficient tritium, and reliably producing net electricity

Generating Electricity from Fusion Energy Requires Meeting Three Scientific/Technological Challenges



<u>Find materials</u> that can handle extreme conditions of reactor

Let's start here

<u>Control, sustain, and predict</u> **a high temperature "burning" plasma to produce neutrons/heat**

<u>Harness fusion power</u> by capturing the energy, breeding sufficient tritium, and reliably producing net electricity

It’s an exciting time for magnetic fusion energy

Sept 2021
CFS and MIT successfully tested new, high-field magnet

Feb 2022
JET tokamak announced new record 59 MJ fusion energy

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JET tokamak announced new record 59 MJ fusion energy

The runway was a tokamak!

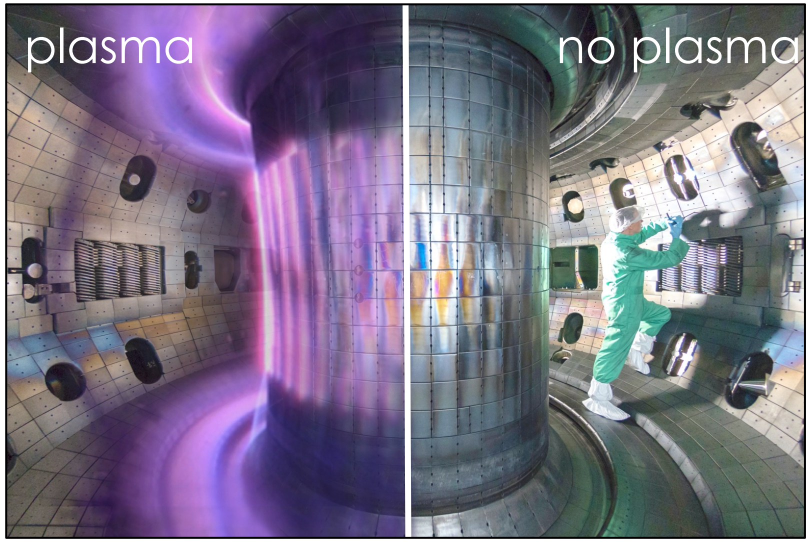
Fusion Energy Inspired
Chloé Spring 2023 Collection

Experiments, along with tremendous progress in predictive capabilities, are paving the way to a burning plasma

Public ⟷ Private ⟷ International

Public

DIII-D Tokamak (San Diego, CA)



no DT (so humans can enter)
tons of diagnostics, upgradable

Private

SPARC

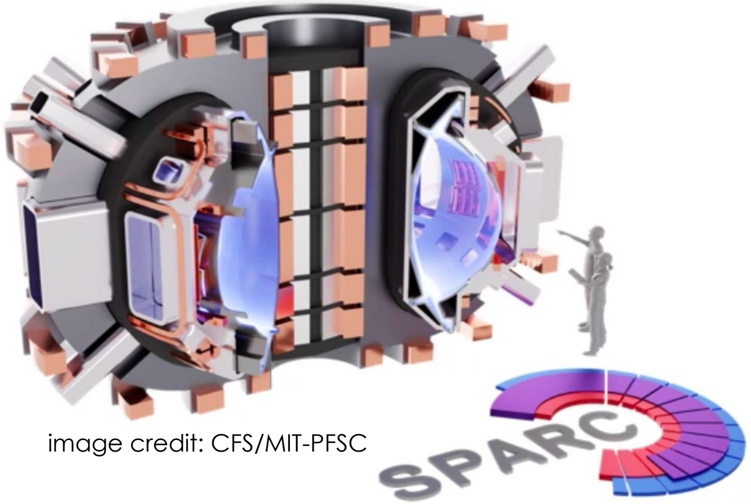
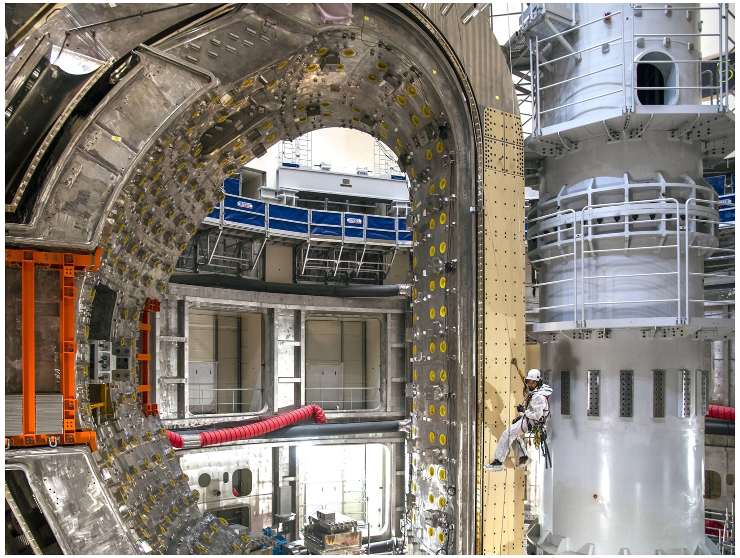


image credit: CFS/MIT-PFSC

DT, Q>1 for 2 s,
planned 2025

International

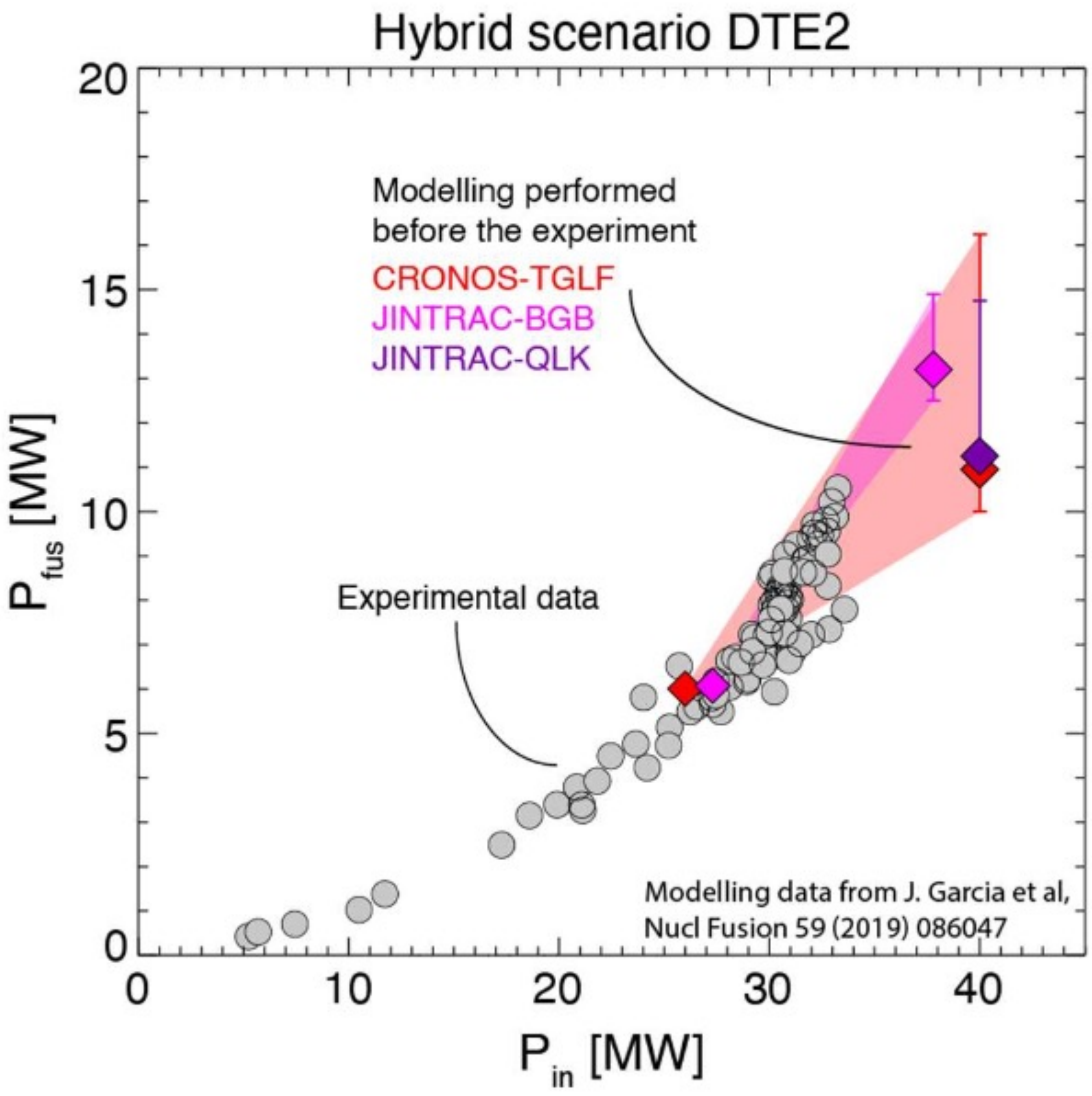
ITER



DT, Q=10 for 400 s, 2035?
power plant scale nuclear facility
35 nations collaborating

Key point: None of these devices will operate in the conditions envisioned for a compact fusion pilot plant → we must extrapolate

Recent JET DT fusion results in broad agreement predictions



- But, Q < 1
- What happens as fusion power becomes dominant?

What Makes a Burning Plasma Unique?

	Fusion Gain	α-Heating Fraction	Scientific Frontier
	$Q = \frac{P_{fusion}}{P_{heat}}$	$f_\alpha = \frac{P_\alpha}{P_\alpha + P_{heat}}$	
Scientific Breakeven	Q = 1	17%	Alpha confinement

plasma transitions from endothermic to exothermic

Endothermic

Exothermic

Highly non-linear behavior can result

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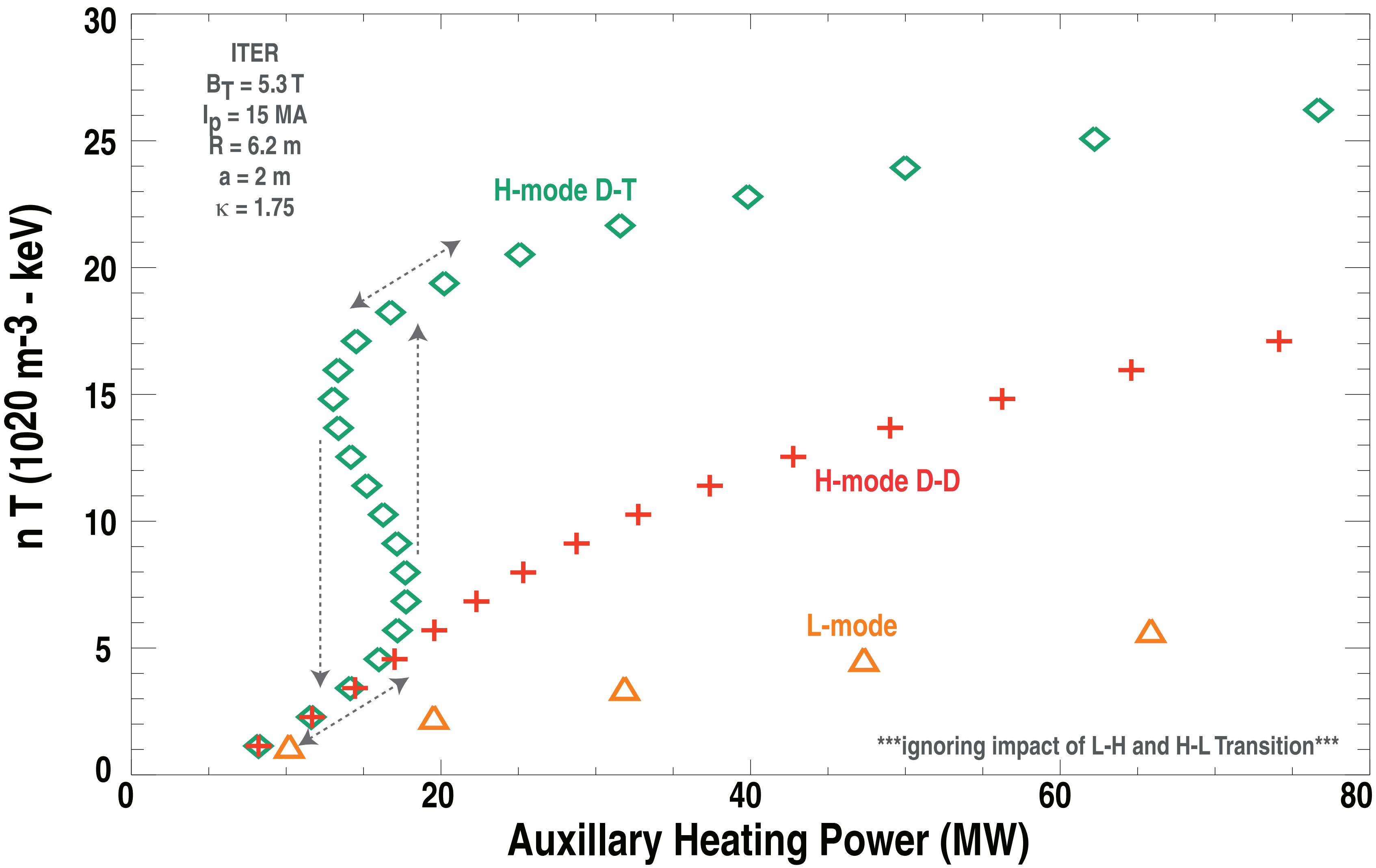
	$Q = \frac{P_{fusion}}{P_{heat}}$	$f_\alpha = \frac{P_\alpha}{P_\alpha + P_{heat}}$	
Scientific Breakeven	Q = 1	17%	Alpha confinement
Burning Plasma Regime	Q = 5	50%	Alpha heating; Alpha effects on energetic particle instabilities
	Q = 10	67%	Strong alpha heating; Non-linear coupling effects
	Q = 20	80%	Burn Control; potentially strong non-linear coupling
	Q = ∞	100%	Ignition

ITER, SPARC

Presence of Alpha Heating Leads to Non-Linear Response of Plasma Energy to Applied Heating



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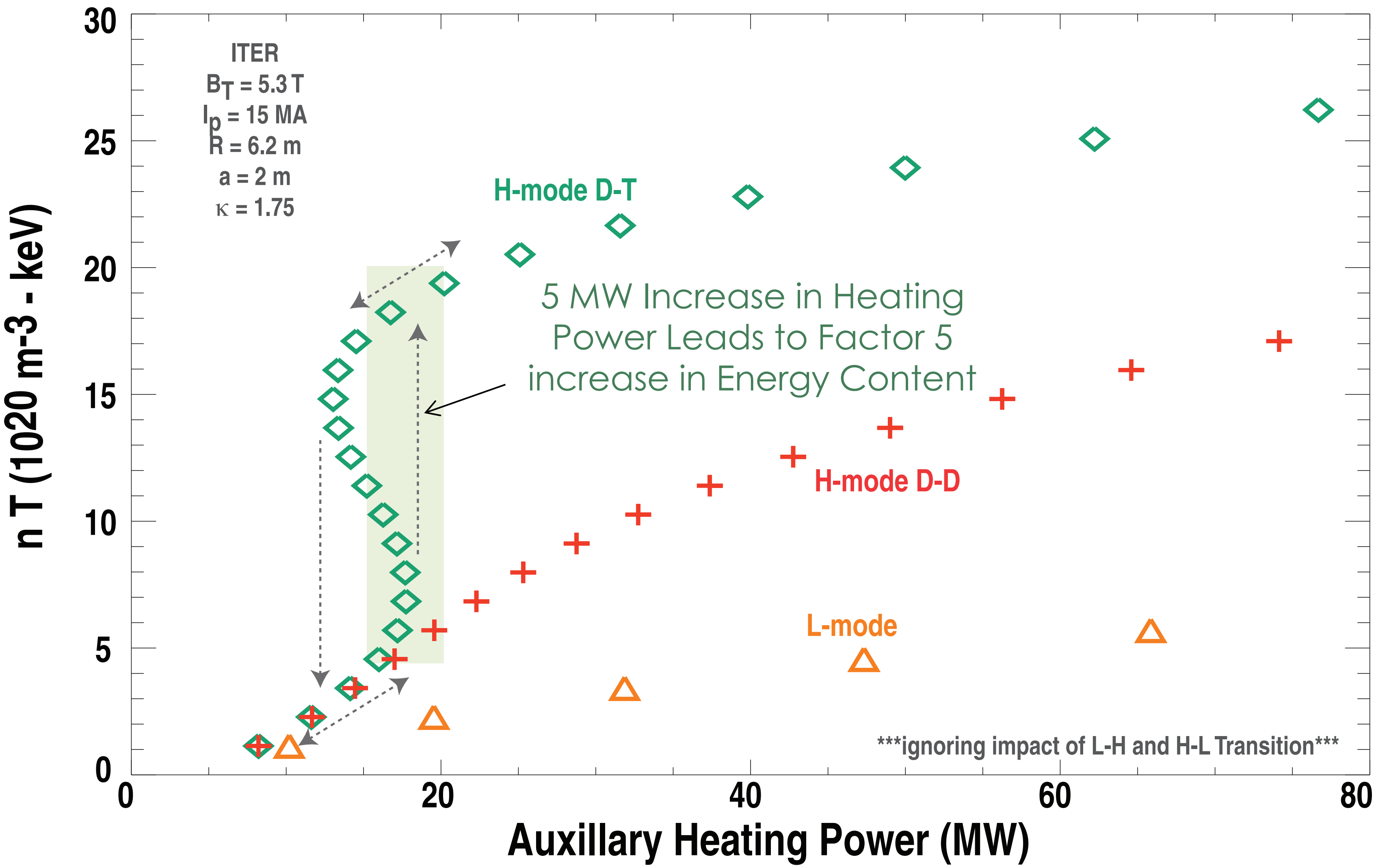
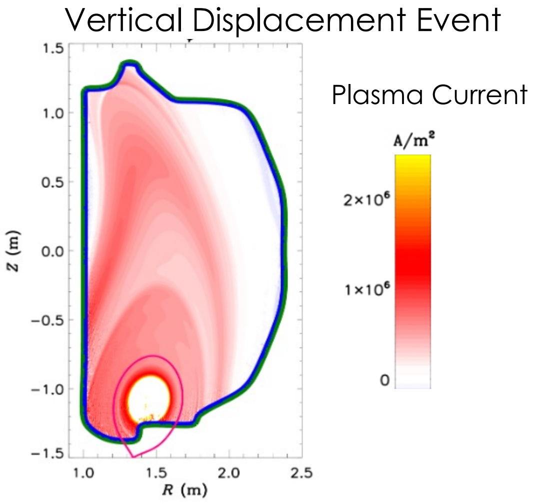


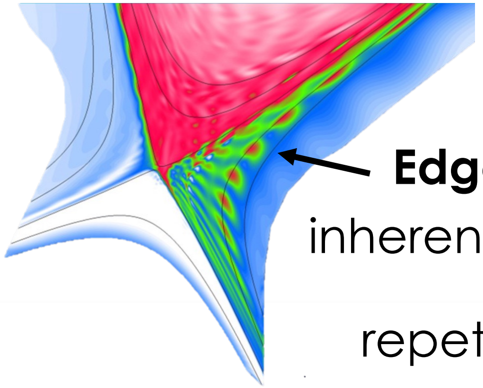
In a burning plasma, increase in plasma temperature → more alpha production → further increase temperature

We’ve made huge progress in understanding tokamak physics ... but there are some outstanding issues



Disruptions

instability causes rapid loss of control, plasma slams into wall



Edge Localized Modes

inherent to ‘high confinement’ (H-mode) repetitive bursts of plasma hit the wall

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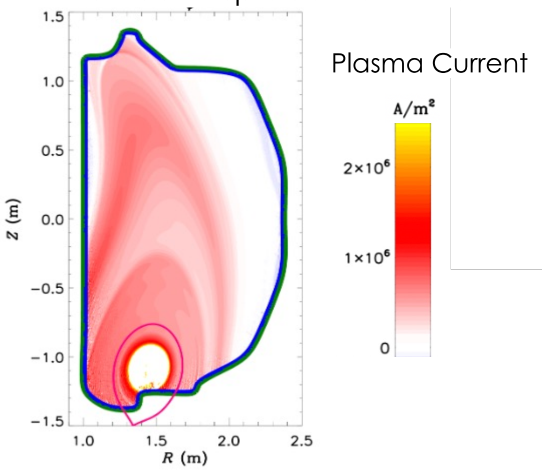
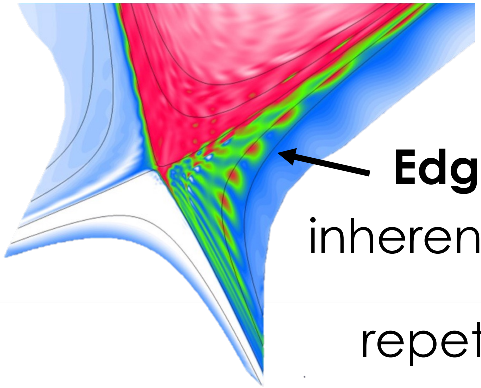
Disruptions

instability causes rapid loss of control, plasma slams into wall

Vertical Displacement Event





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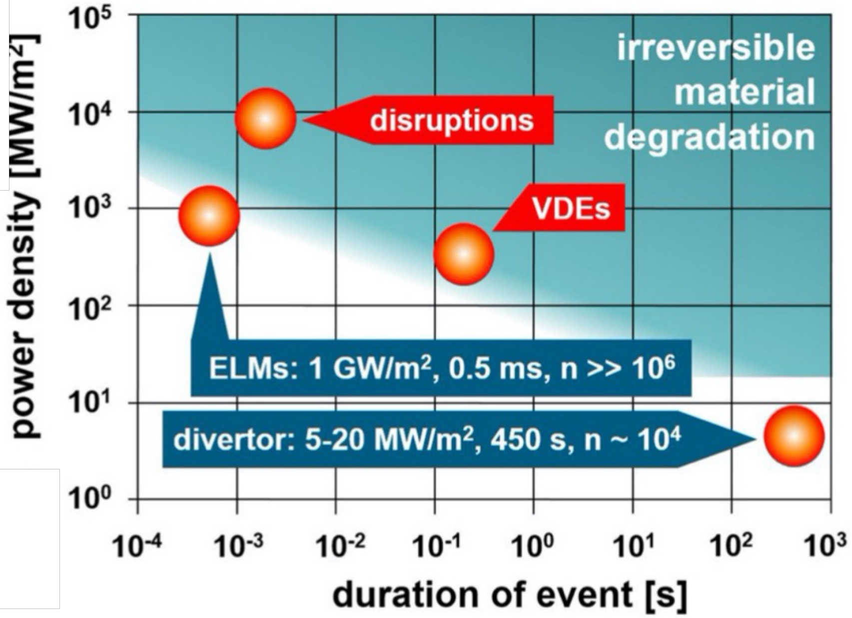
repetitive bursts of plasma hit the wall

Transients are very bad for reactors…



J. Linke, Matter. Radiat. Extremes 4 (2019) 056201

melting, coolant leaks, expensive repairs, downtime

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Disruptions

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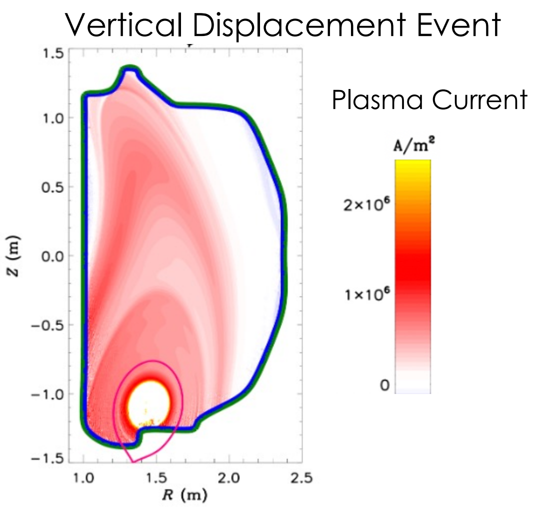
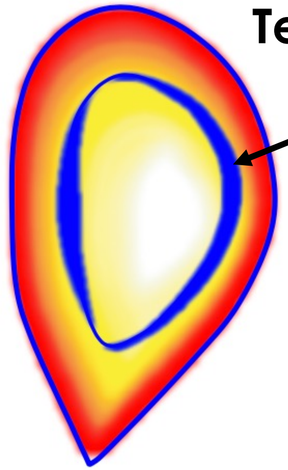
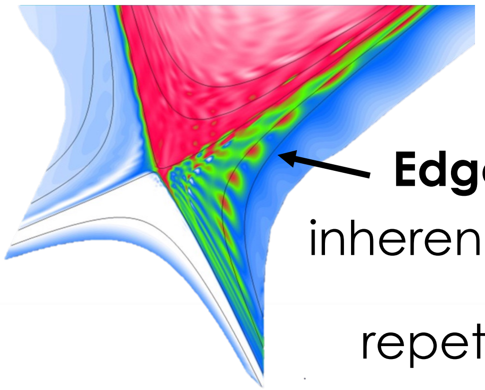




Tearing Modes

cause local transport/cooling, decreased fusion performance (or worse, grow & cause disruptions)



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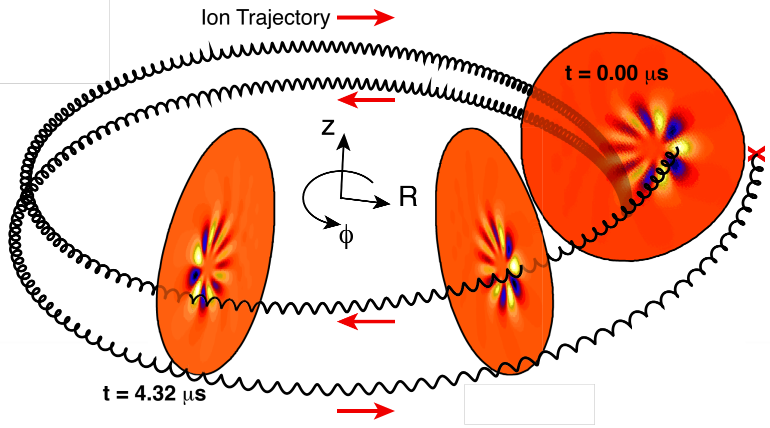


Fast-Particle Instabilities

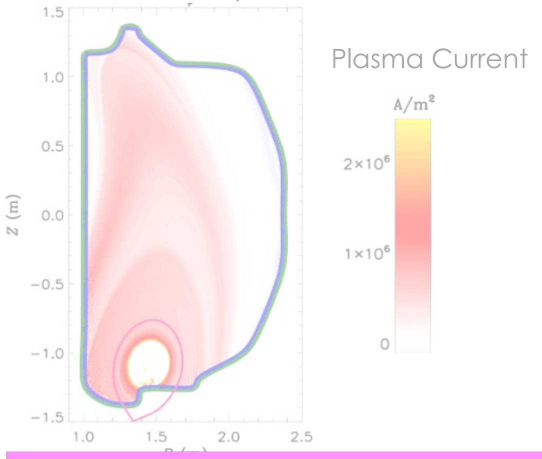
electromagnetic waves disturb orbits, cause redistribution or loss of alphas, reduce plasma performance

We've made huge progress in understanding tokamak physics ... but there are some outstanding issues

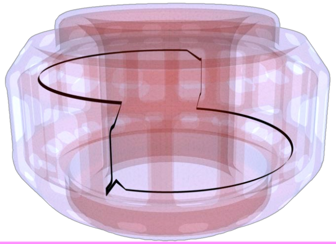
We may be able to control or mitigate, but it increases cost → avoidance is ideal

Disruptions

inject frozen pellets



Install coils in the walls



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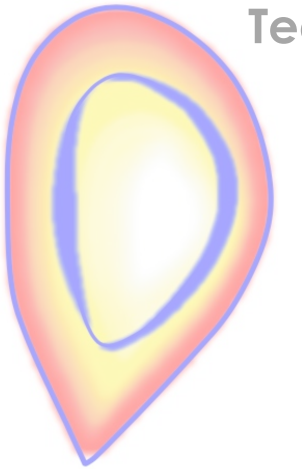
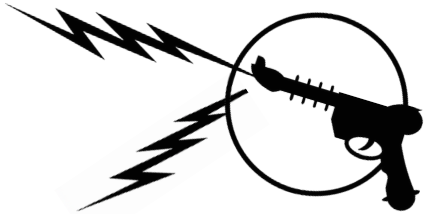
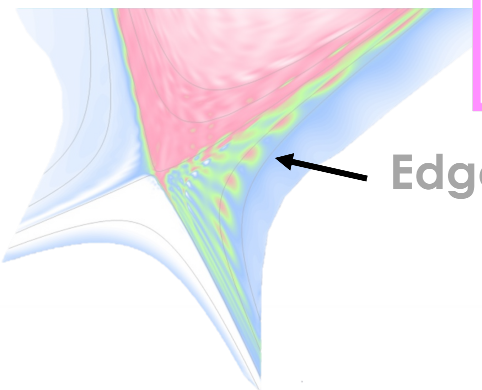


inject microwaves to control plasma profiles





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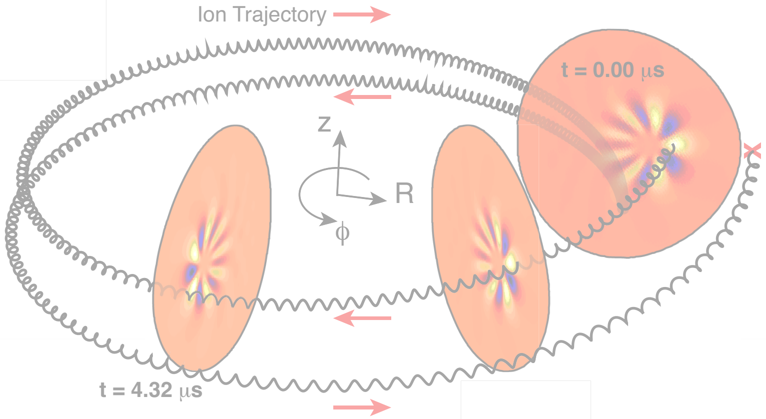
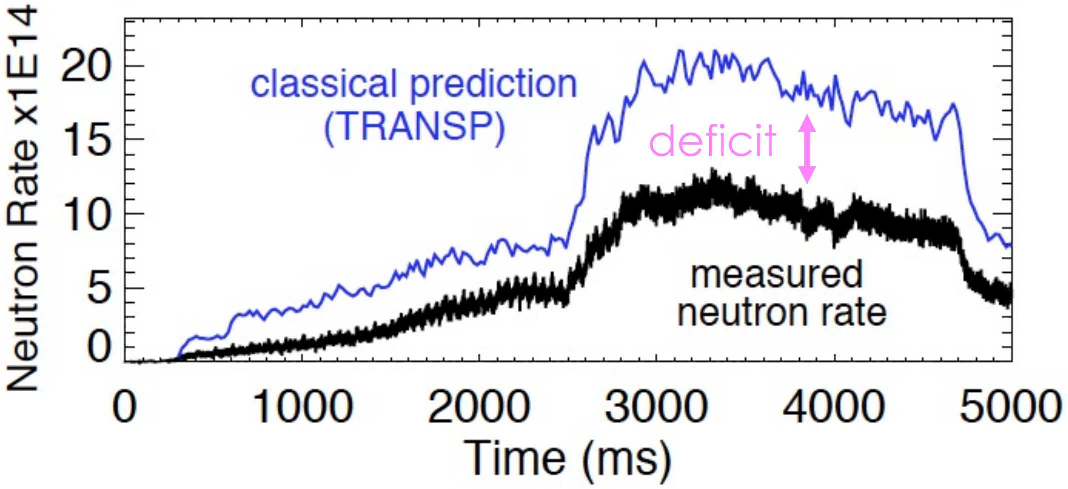


Fast-Particle Instabilities

Example: Fast-ion instabilities can limit performance & affect requirements for (expensive) external control systems

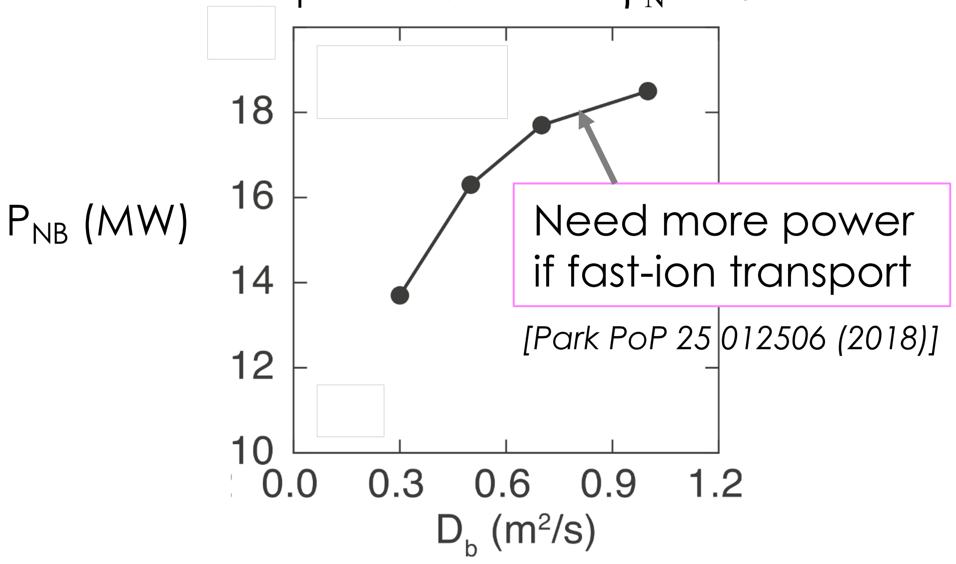
- In DIII-D, Alfvén Eigenmode induced fast ion transport limits our ability to achieve steady state scenarios *[Holcomb, PoP 22 (2015)], [Heidbrink, PPCF 56 (2014)]*

neutrons are volumetric proxy for fast-ion confinement



→deficit due to AE's transporting fast ions

Neutral Beam Power Required to Reach β_N ~4.6



Assumed Fast-Ion Transport

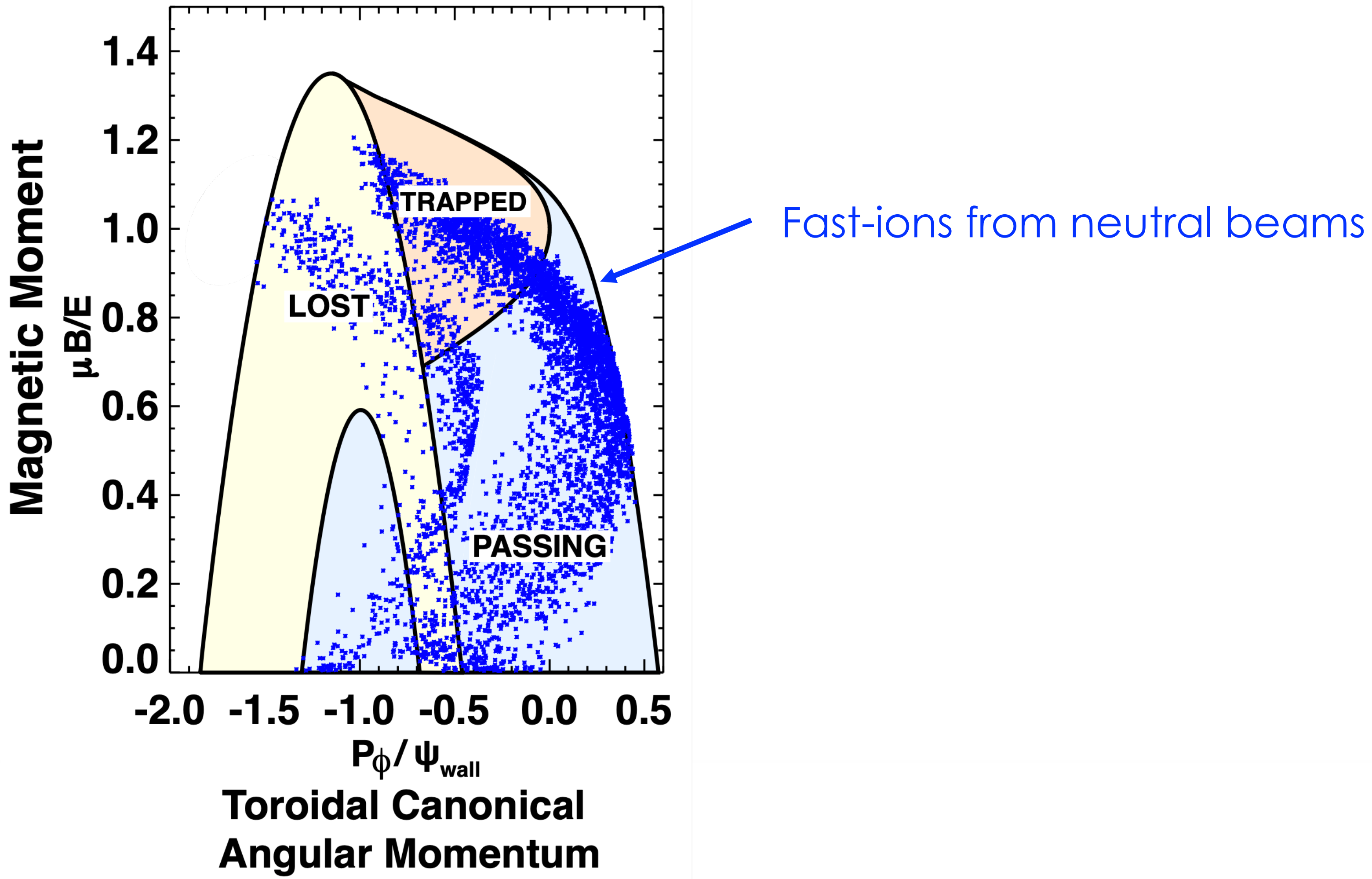
In DIII-D we've done experiments to control AEs (by changing current and fast-ion profiles) and improved fusion performance (β_N) by 15 % *[Collins, IAEA (2021)]*

… **but do you need/want to control AEs in a reactor**?

Basics of Energetic Particle Transport

EPs are best treated as single particles: collisions are rare, distribution function is complicated

Map of Orbit Topology Space



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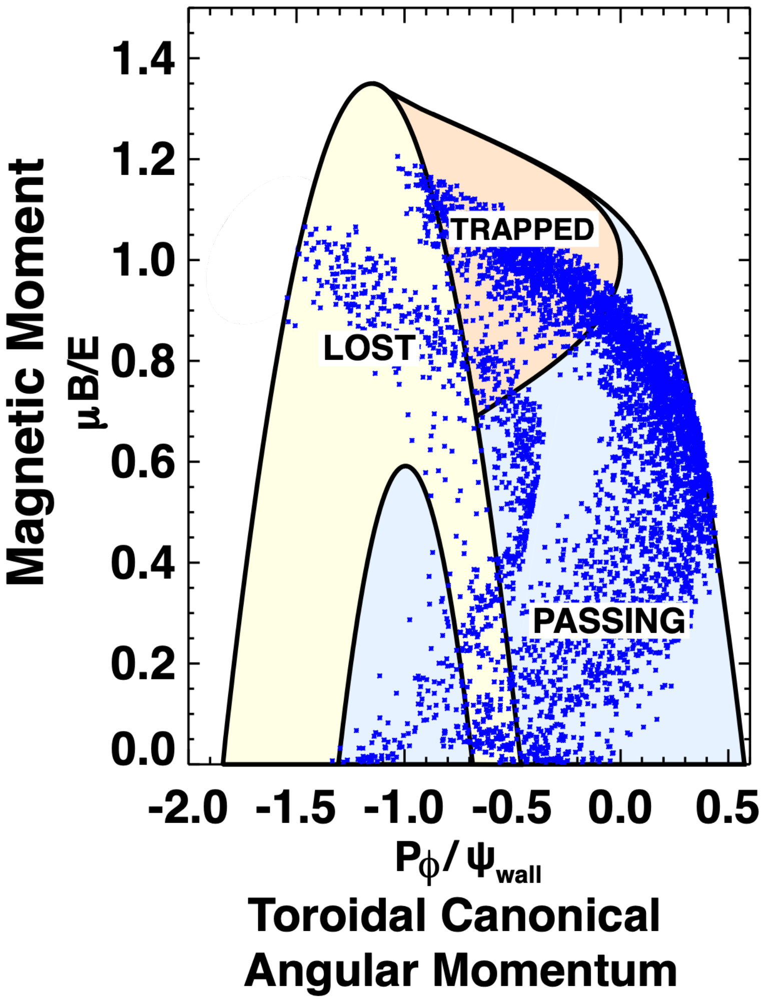
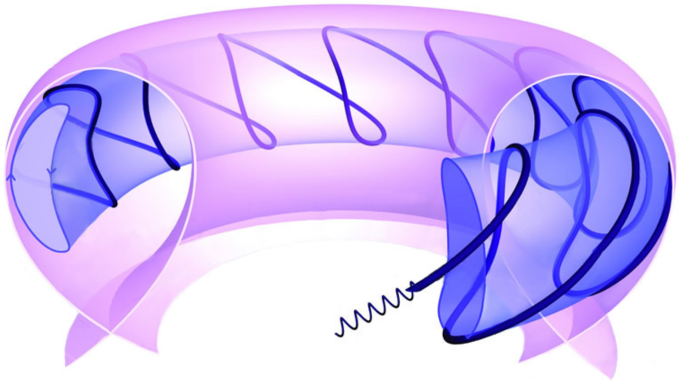
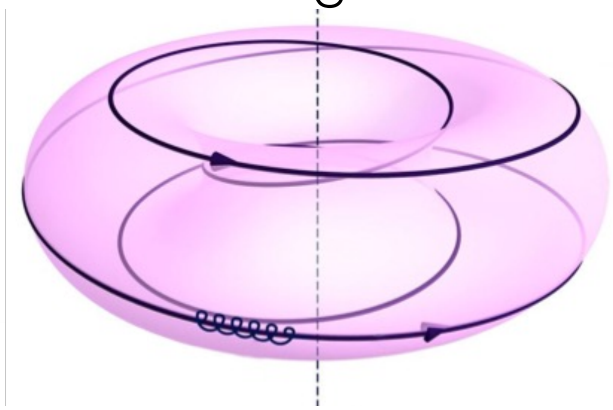


Trapped orbit



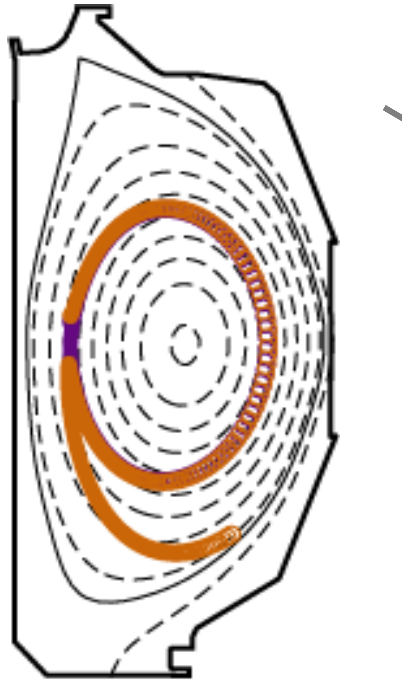
Passing orbit



Basics of Energetic Particle Transport

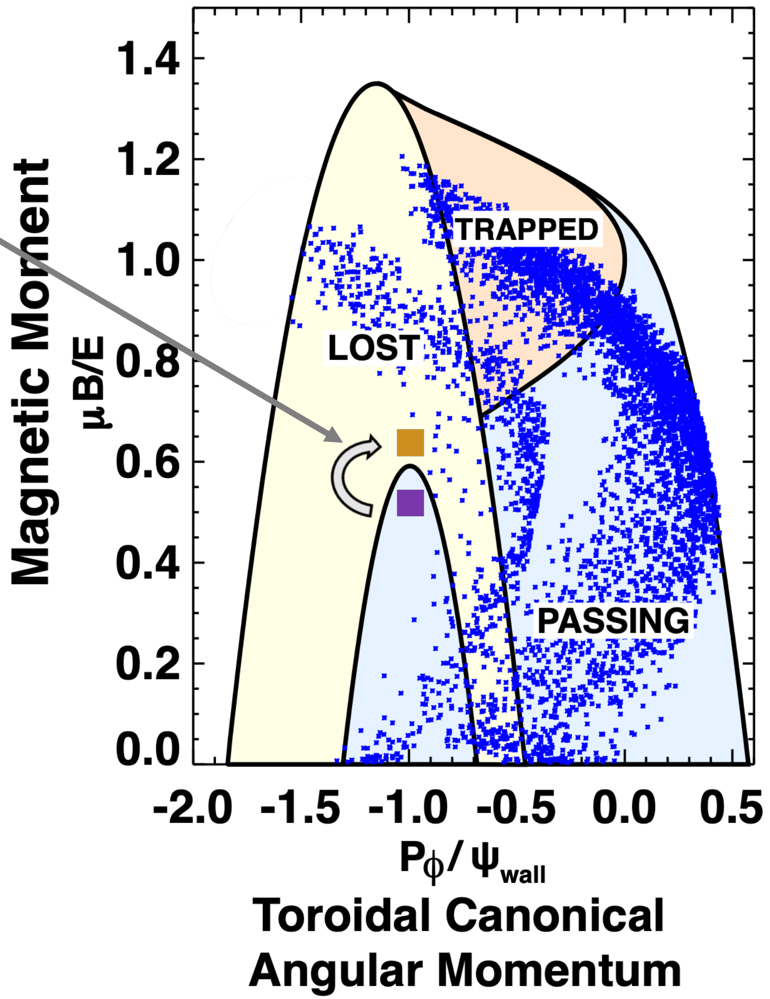
EPs are best treated as single particles: collisions are rare, distribution function is complicated

Small change in E, P_ϕ can lead to big change in orbit



Projection of 80 keV D^+ orbit in DIII-D

Map of Orbit Topology Space

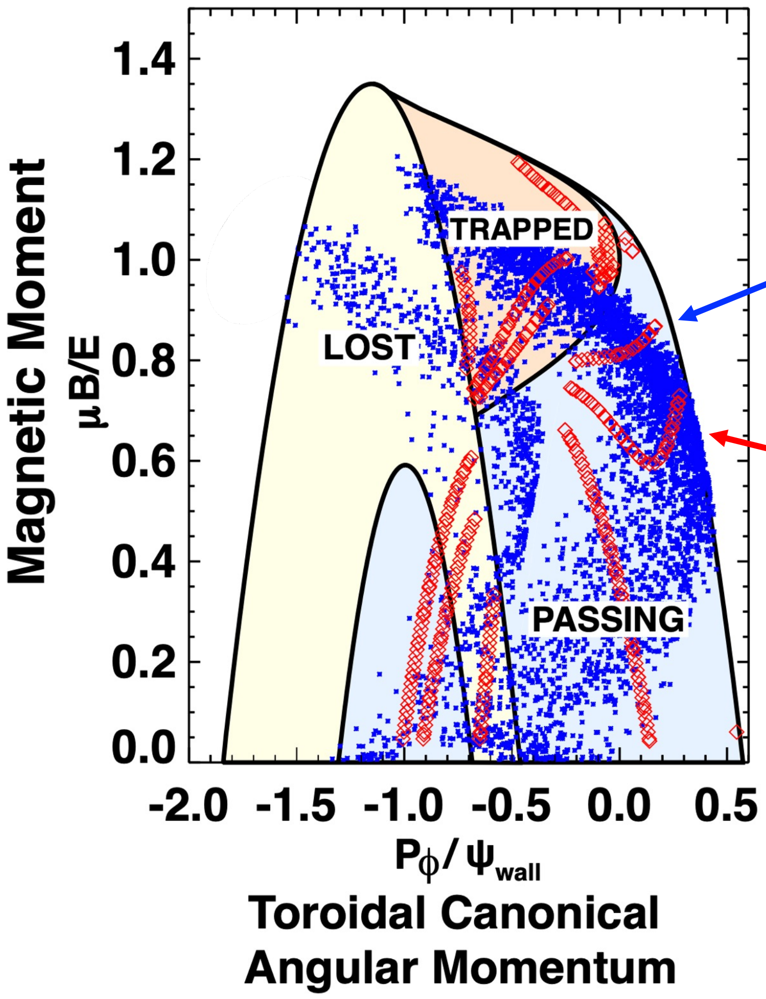


AEs are driven by gradients in phase space

$$\frac{\gamma_{\mathrm{EP}}^{\mathrm{drive}}}{\omega} \propto \beta_{\mathrm{EP}} \left(\frac{n}{\omega} \frac{E}{f} \frac{\mathrm{d}f}{\mathrm{d}P_{\varphi}} + \frac{E}{f} \frac{\mathrm{d}f}{\mathrm{d}E} \right)$$

Growth rate
driven by gradients
in space and energy

Map of Orbit Topology Space



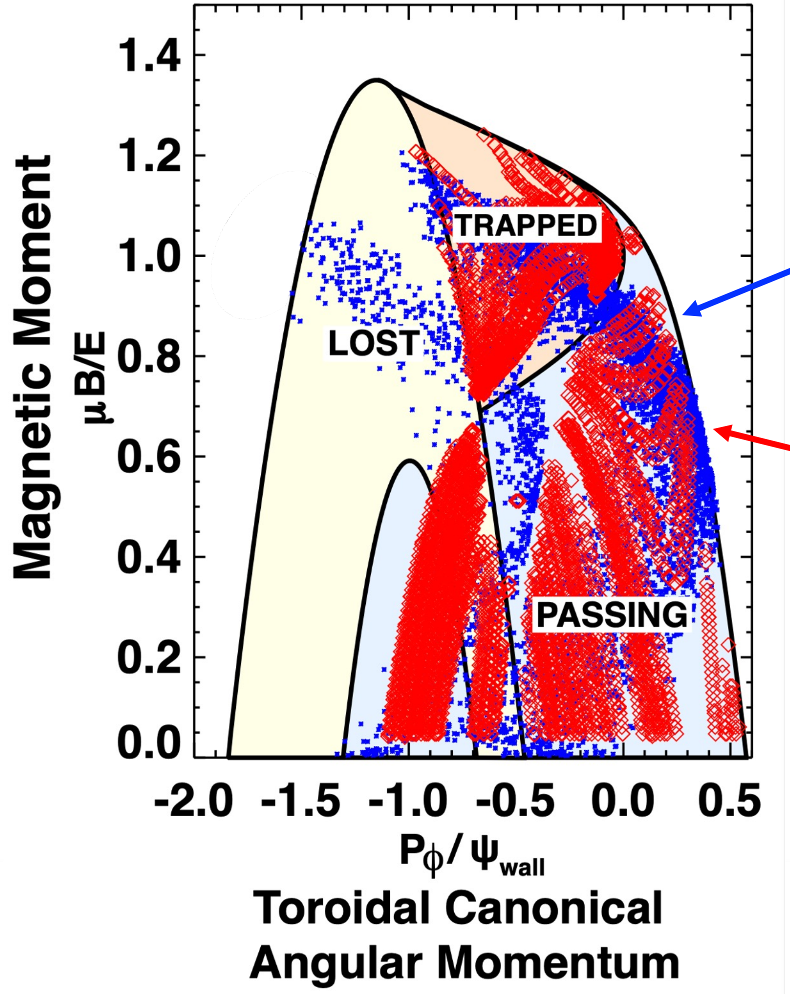
Fast-ions from neutral beams

Locations of possible wave-particle energy exchange (**<u>single AE mode</u>**)

Transport occurs when AEs resonate with fast ions

Whether or not AEs cause significant transport depends on number of fast ions in that part of phase space.

Map of Orbit Topology Space



Fast-ions from neutral beams

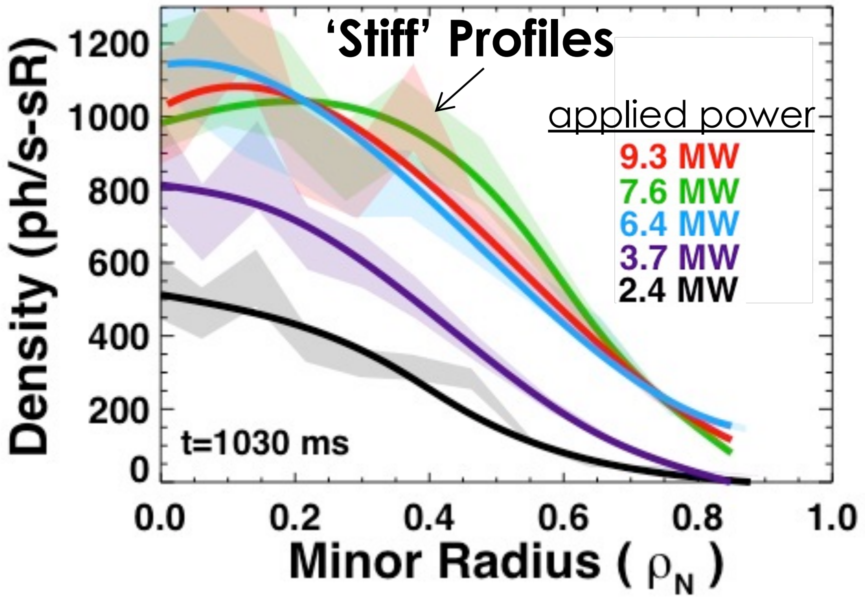
Locations of possible wave-particle energy exchange (**multiple AEs**)

A lot of AEs → a lot of transport of fast ions

Many overlapping AEs cause ‘stiff’ critical gradient transport

[Collins PRL 116 (2016)]

Fast Ion Density Measurements



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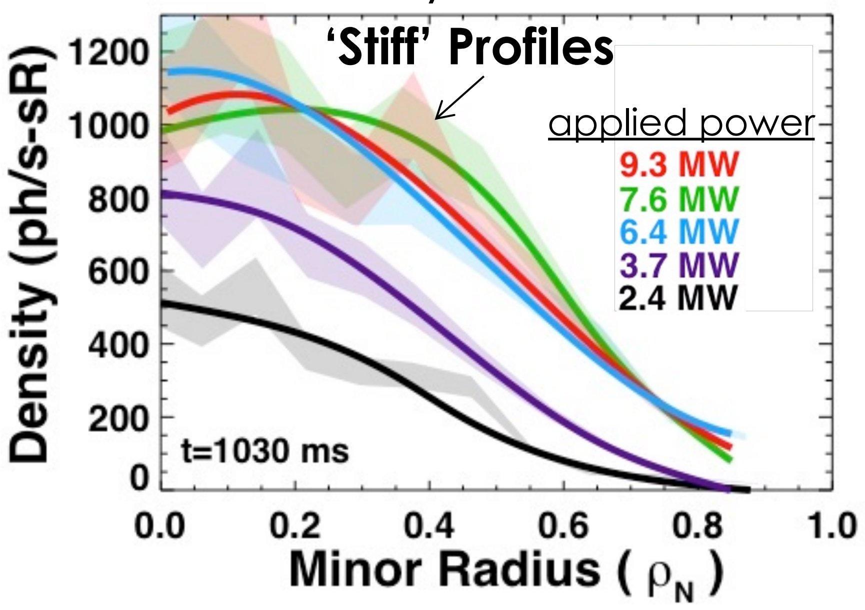
Fast Ion Density Measurements



cause: critical gradient transport

- Critical gradients are ubiquitous phenomenon in nature:
  → gradients drive instabilities
  → particles are transported which limits the gradient
  → instabilities stop growing ('marginal stability')

The frontier for energetic particle physics: Predict the impact of fast ion transport in fusion pilot plant design

Increasing complexity, physics fidelity, computational cost

Critical gradient models

TGLF-EP+ALPHA
Bass and Waltz,
PoP 24, 122303 (2017)

RBQ-1D
Gorelenkov et al.,
NF 58 082016 (2018)

Kick model

Podestá et al.,
PPCF 56 055003 (2014)

MEGA model

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NF 52 033003 (2012)

Fully nonlinear, first-principles transport model. Not yet successfully implemented.

preserve velocity space dependence

The frontier for energetic particle physics: Predict the impact of fast ion transport in fusion pilot plant design

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preserve velocity space dependence

Fast, can check
- Will modes be unstable?
- How much impact will transport have on the scenario?

Good for initial reactor design.

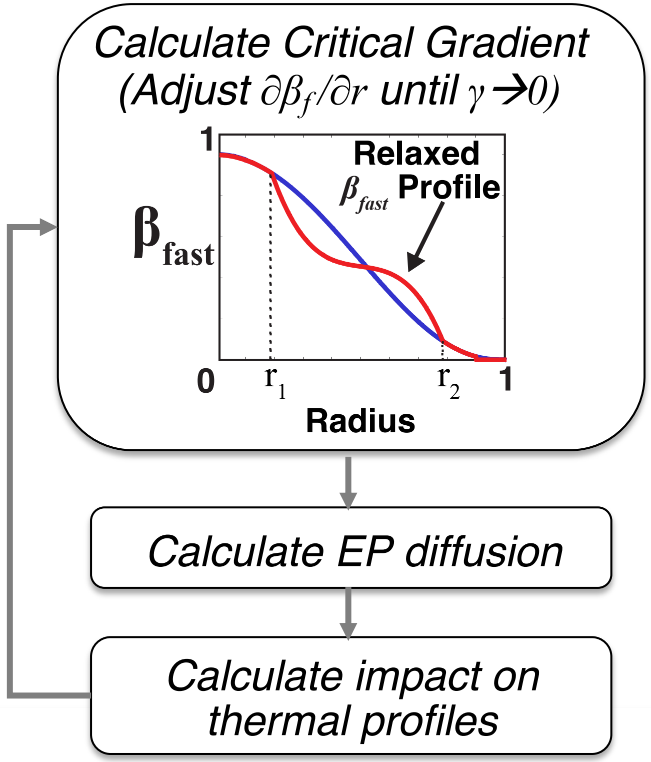
Precise, can check
- Will lost fast ions cause hot spots on the wall?
- How much is current drive and torque affected?

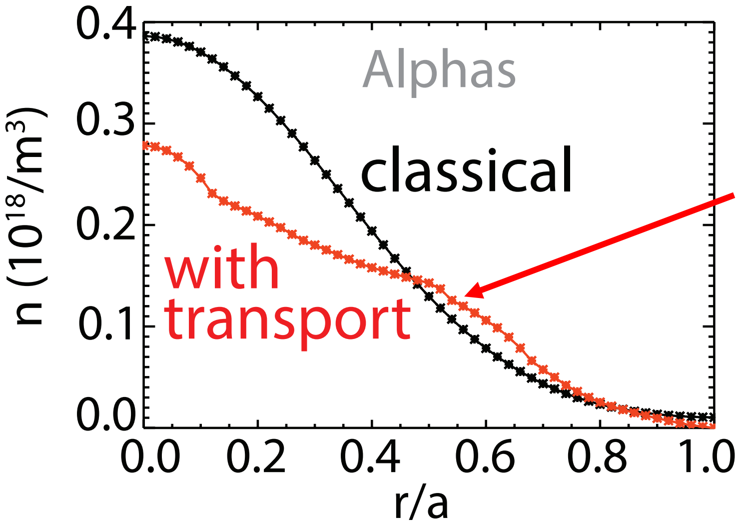
Good for fully vetting an operating point.

The frontier for energetic particle physics: Predict the impact of fast ion transport in fusion pilot plant design

Increasing complexity, physics fidelity, computational cost

Critical gradient models



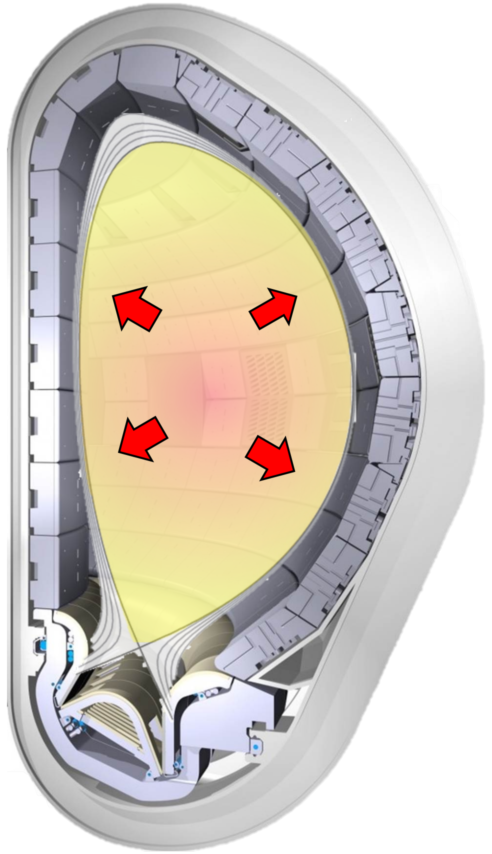


Models have predicted significant fast-ion transport in ITER *[E.M. Bass, IAEA (2018)]*

- **Pilot plant studies have not traditionally included physics-based EP transport!**
  – Need to know alpha heating efficiency, losses (3.5 MeV alphas to walls will probably destroy stuff)

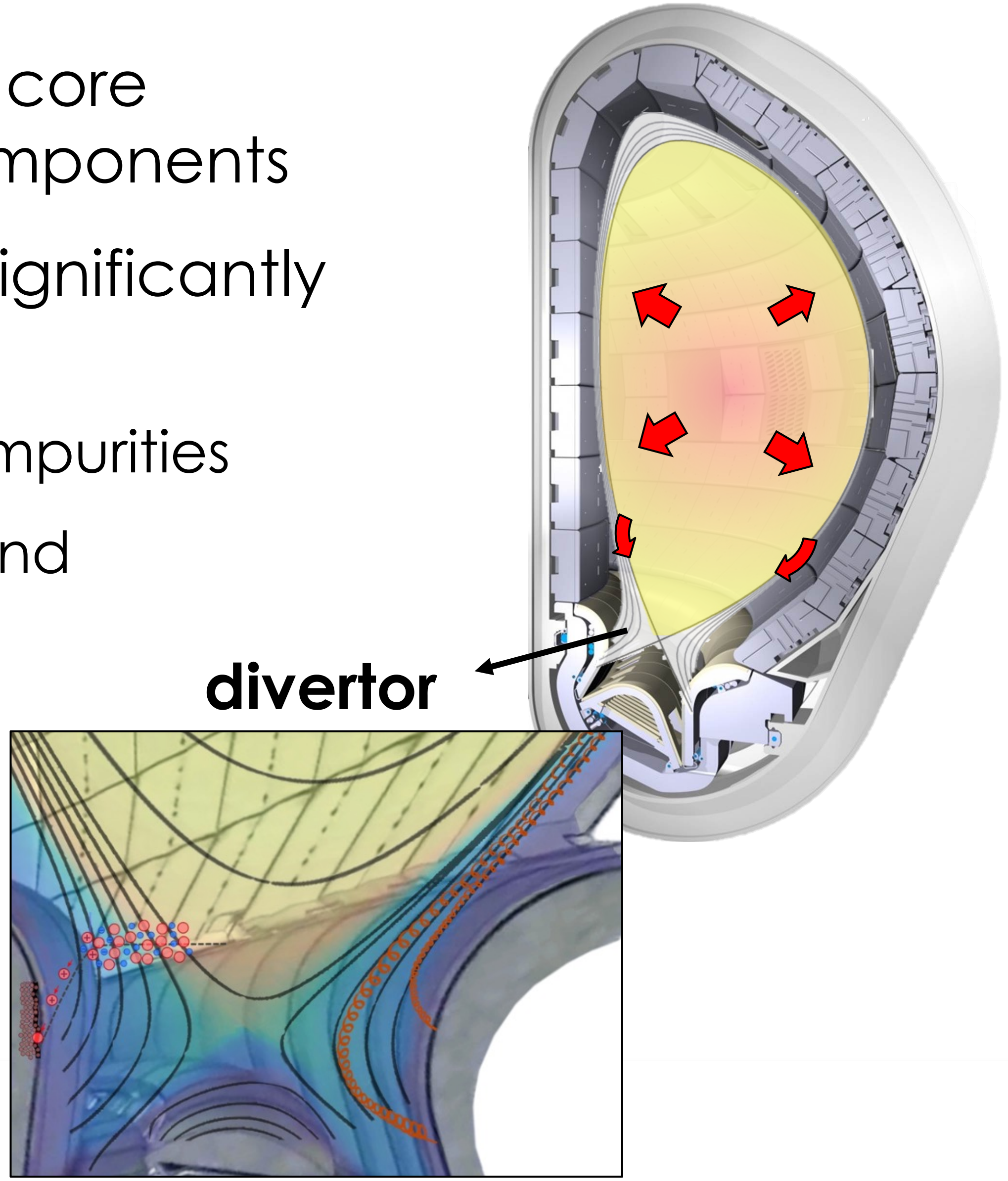
Handling the power flowing out of the plasma is a serious challenge

- Plasma particles and energy leak out of the core plasma and interact with plasma-facing components



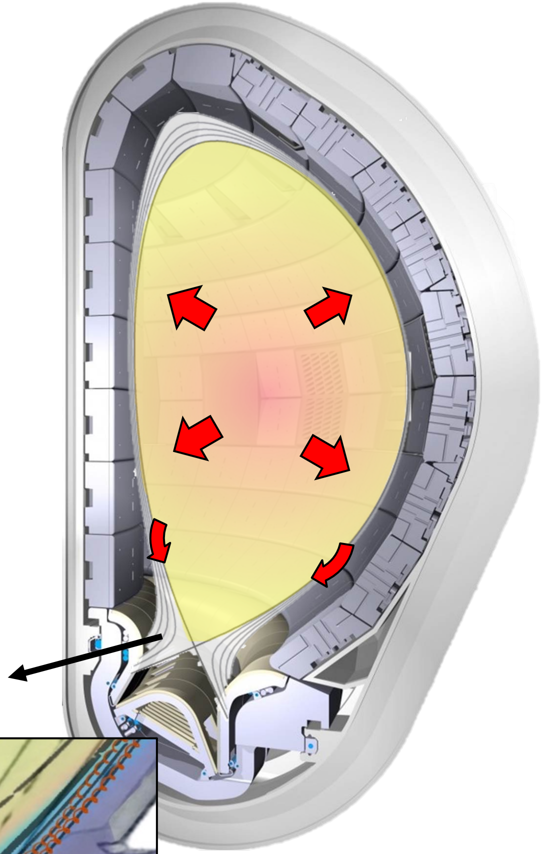
Handling the power flowing out of the plasma is a serious challenge

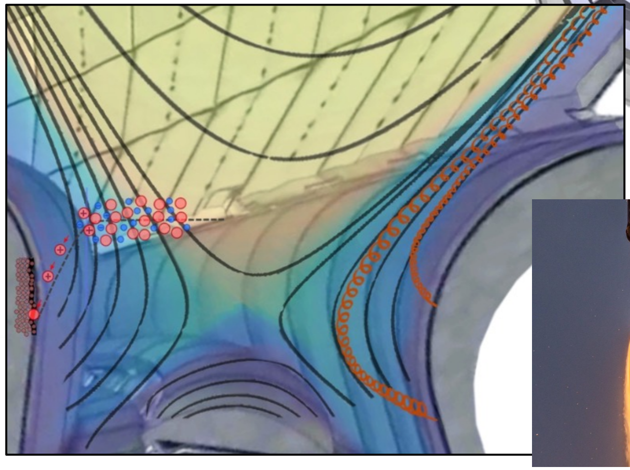
- Plasma particles and energy leak out of the core plasma and interact with plasma-facing components
- Escaping particles channeled to a divertor significantly increases fusion performance
  - Reduces contamination of core plasma by impurities
  - Allows better control of the plasma density and removal of He ash by pumping



Handling the power flowing out of the plasma is a serious challenge

- Plasma particles and energy leak out of the core plasma and interact with plasma-facing components
- Escaping particles channeled to a divertor significantly increases fusion performance
  - Reduces contamination of core plasma by impurities
  - Allows better control of the plasma density and removal of He ash by pumping
- BUT heat fluxes on material surface can exceed a rocket nozzle (>10 MW/m^2)
- Long time-scale operation (> 30 s) only possible with effective mitigation measures and excellent surface cooling

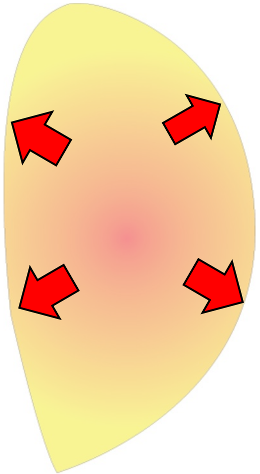




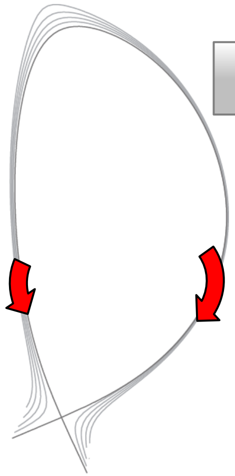
Issues need to be solved in an integrated way, not in isolation: The plasma scenario & compactness will be limited by engineering

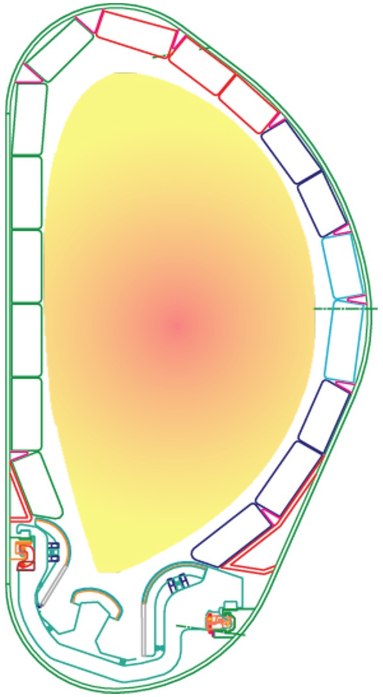
Control, sustain, and predict

- **Core**:
  - Generate heat/neutrons from fusion reactions
  - Contain energy as long as possible
  - Produce optimized state w/ weak control



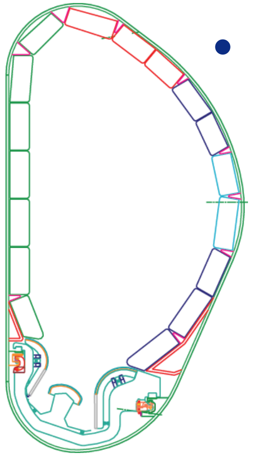
- **Edge/Scrape-Off Layer:**
  - Don't melt the (thin) wall
  - Don't pollute the core



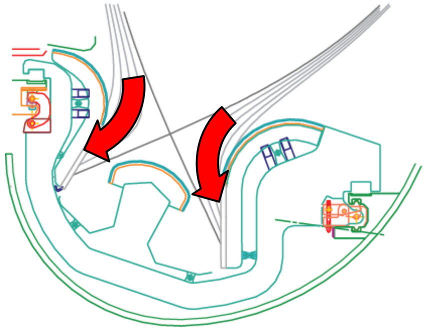


Find materials

Harness fusion power

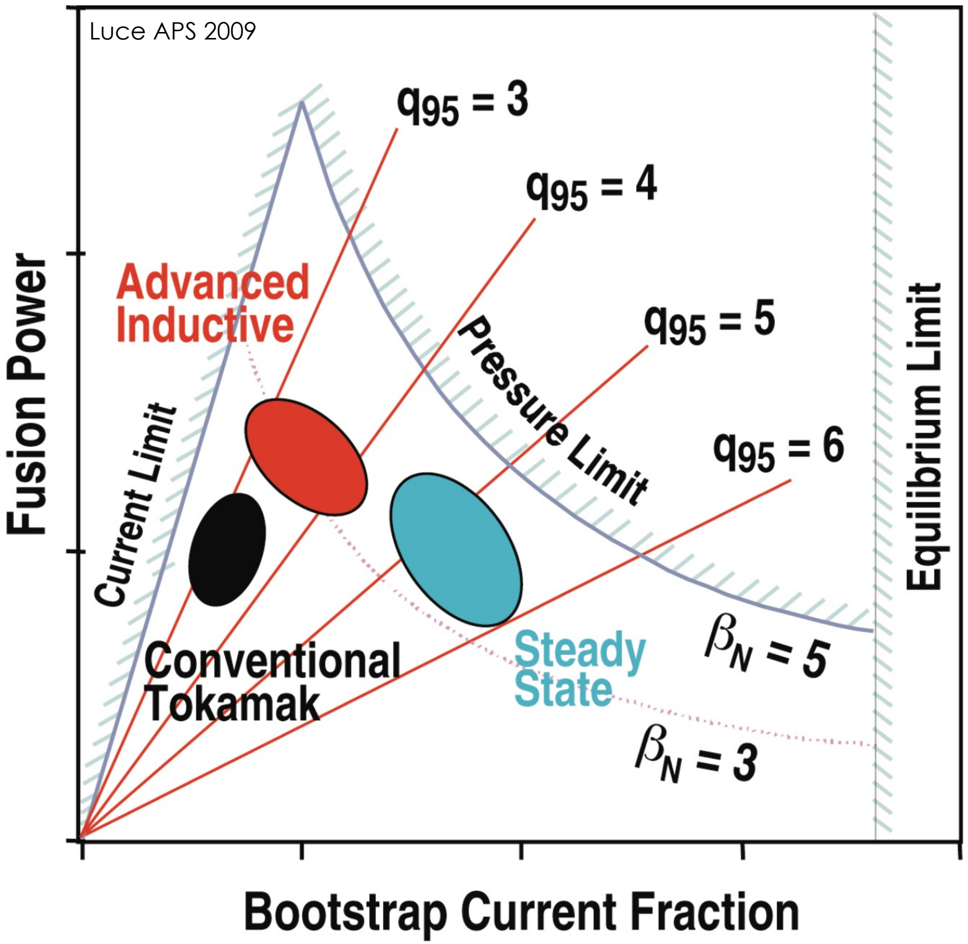


- **Blanket:**
  - Needs to breed tritium (so don't want too many holes for heating & current drive)
  - Extract heat
  - Shield magnets from neutrons



- **Divertor:**
  - Exhaust helium "ash"
  - Dissipate heat
  - Shield eroded materials from core

We are working to find better tokamak operating points



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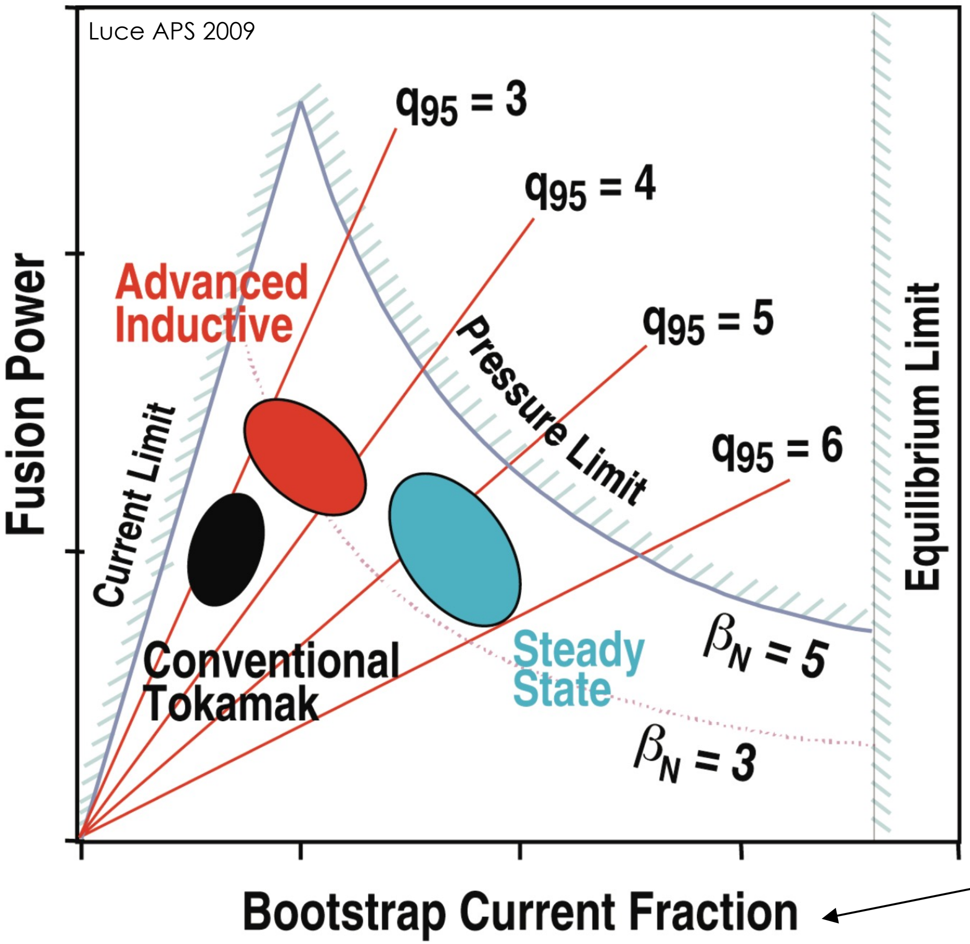
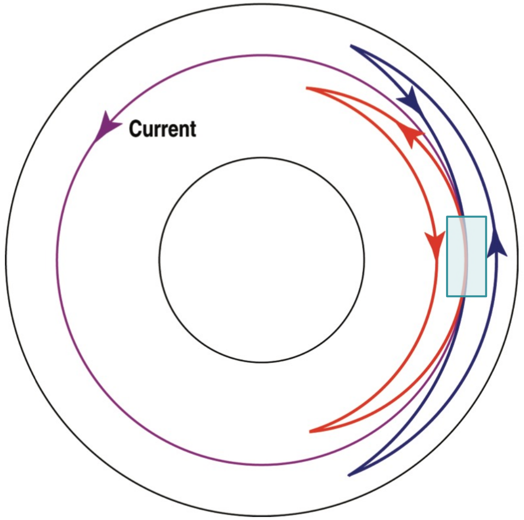


(Plasma creates its own current!)

The Amazing Bootstrap Current: Due to gradients in density and temperature, more trapped particles move in the toroidal direction, driving current.



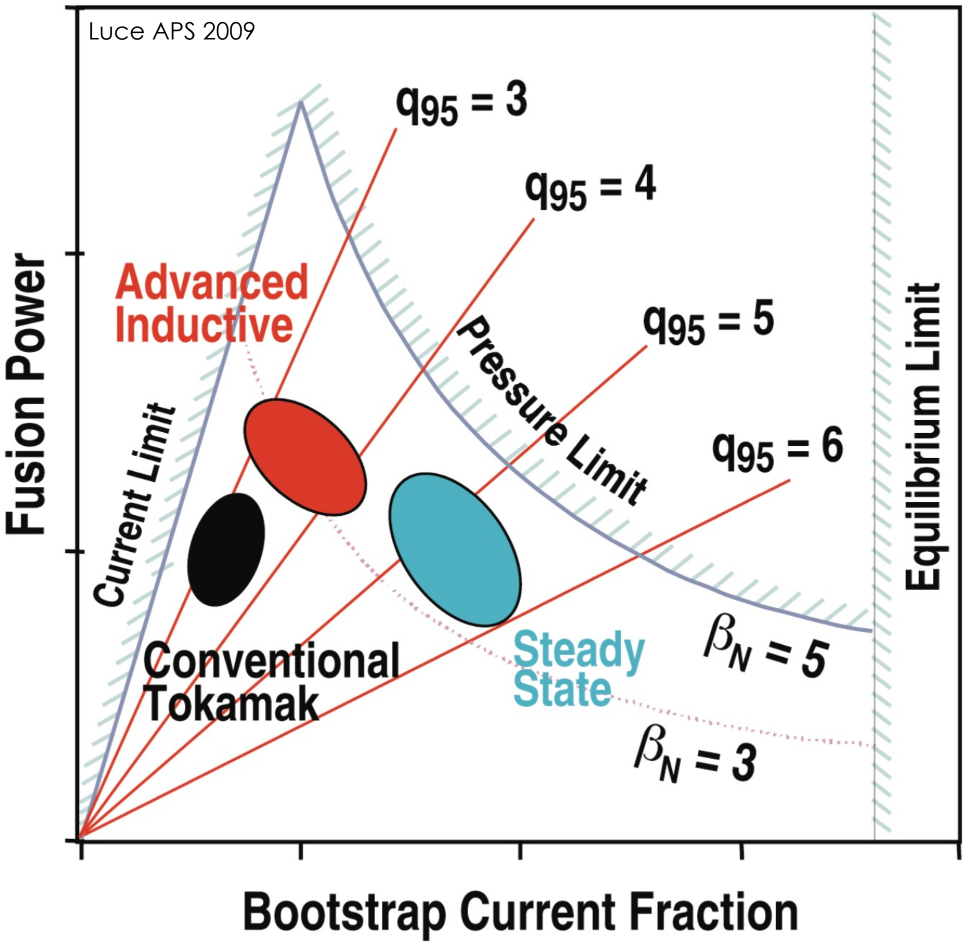
Tokamak top view of trapped ion orbits

We are working to find better tokamak operating points

$$P_{fus} = c_1 \frac{\beta_N^2 B_t^4 R_0^3}{q_{95}^2 A^4}$$

β_N :
ratio of thermal/magnetic pressure

q:
ratio of field line toroidal/poloidal turns
(high current → low q)



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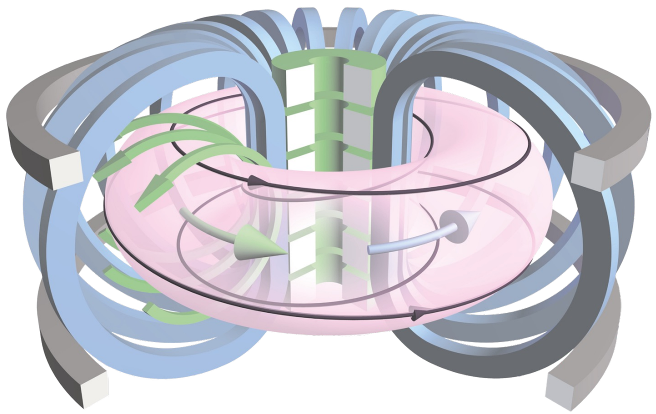
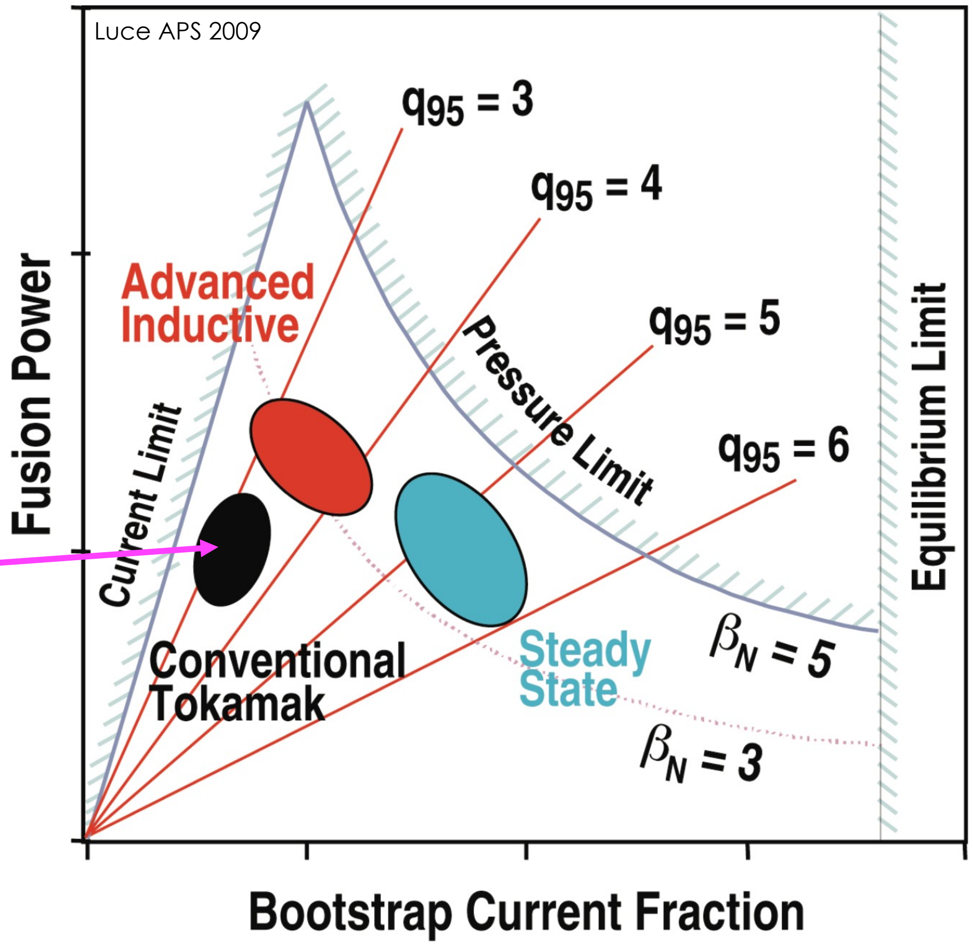


pulsed: ramp
central solenoid

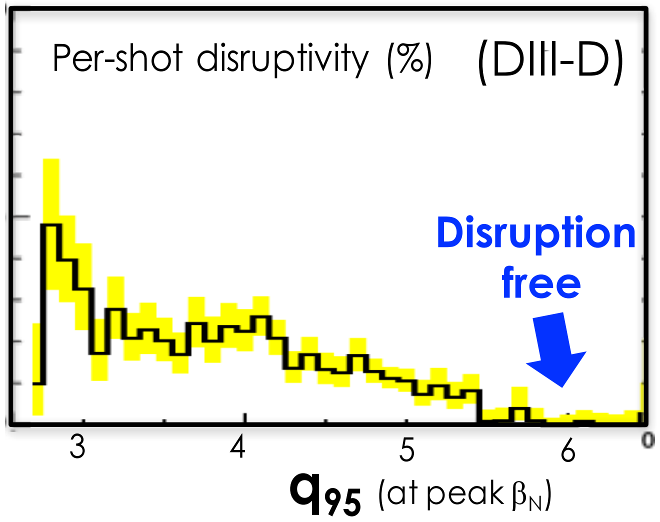
i.e. ITER, SPARC



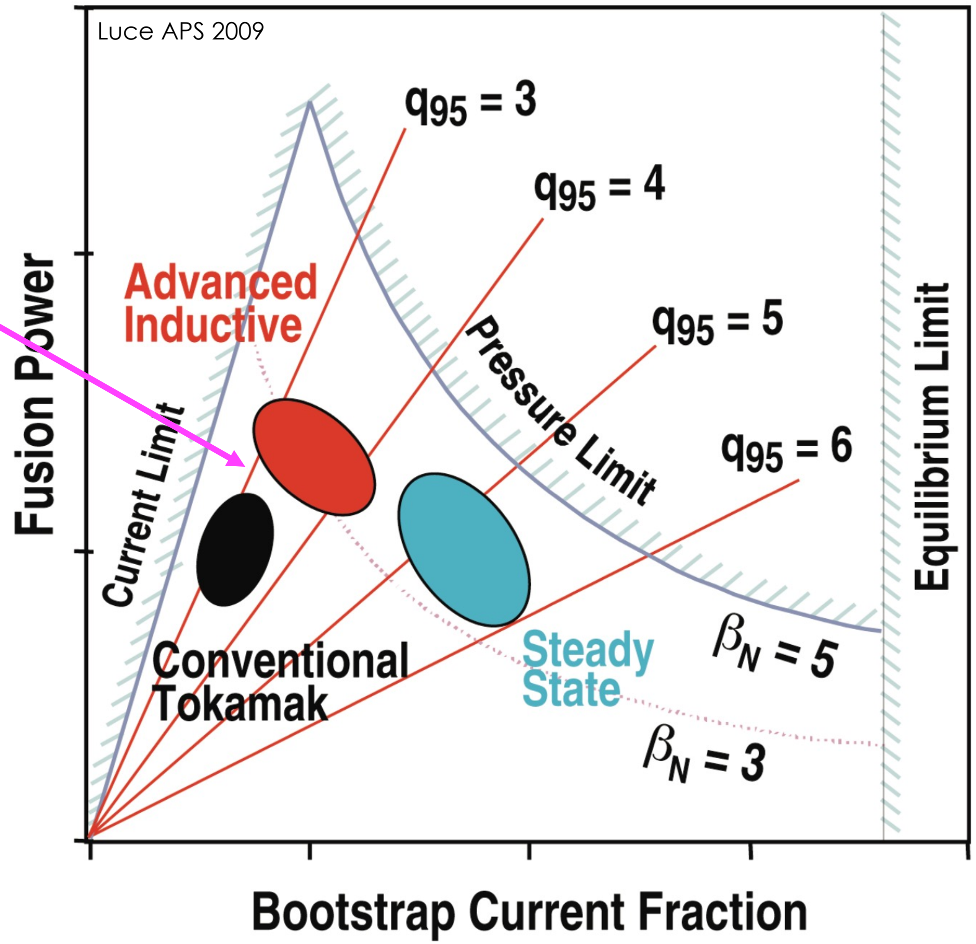
steady-state: all current is externally applied or self-driven (no ohmic current induced by solenoid)

We are working to find better tokamak operating points

high fusion power, but
prone to disruptions because
near plasma current limit



"safety factor"



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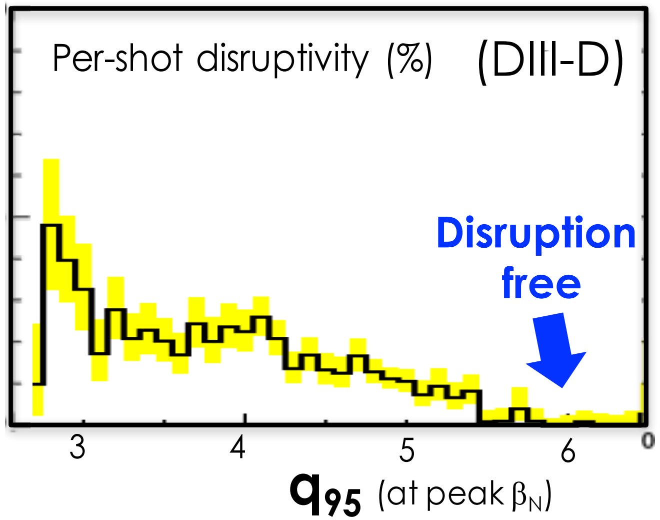

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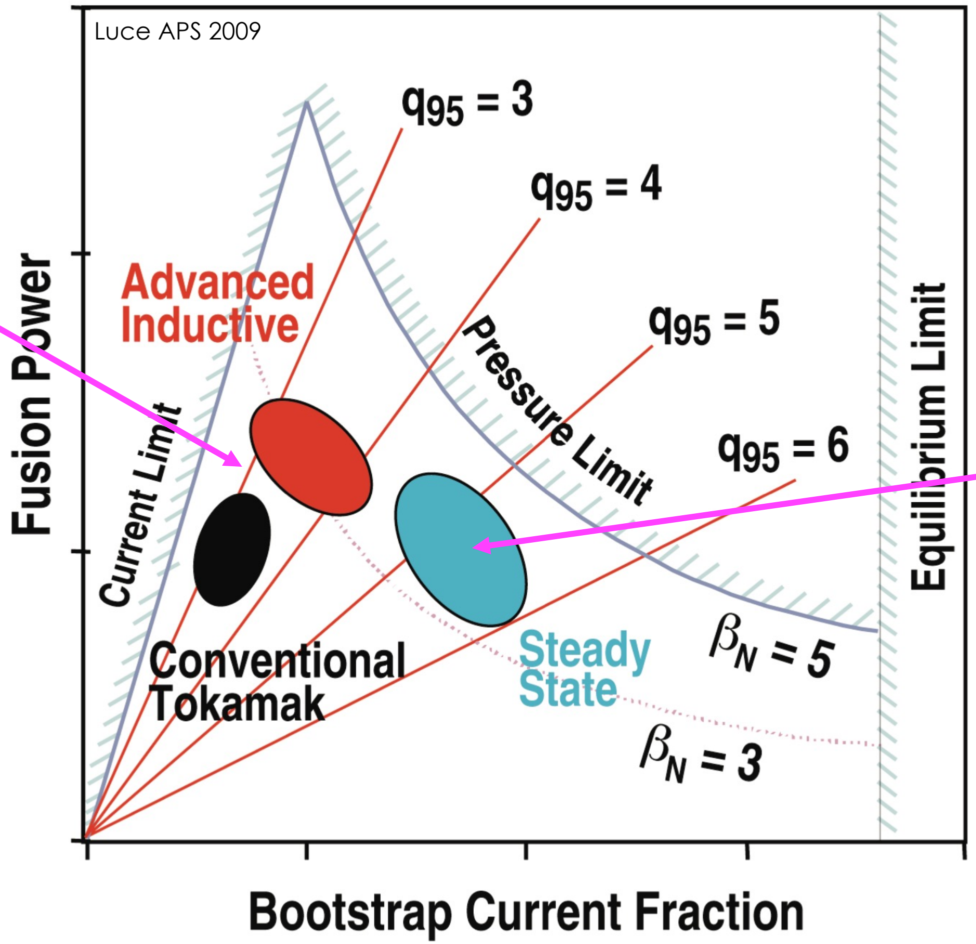
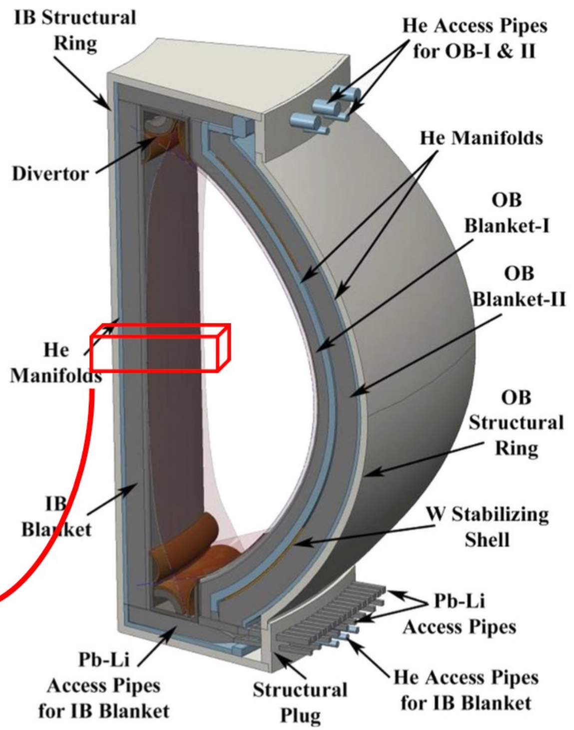


Here, it's hard to get to high plasma pressure (β_N)

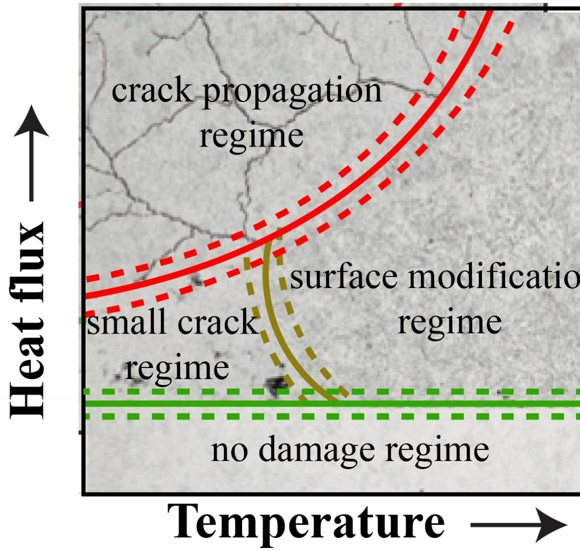
But steady state could lead to a more reliable reactor
-less input power
-avoids cyclic stress

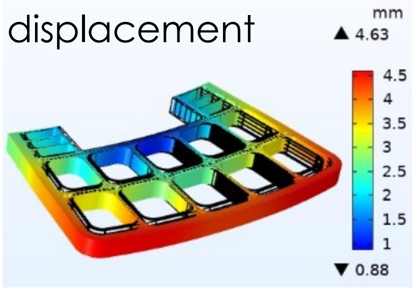
Example: Pulsed or Steady-State Tokamak?

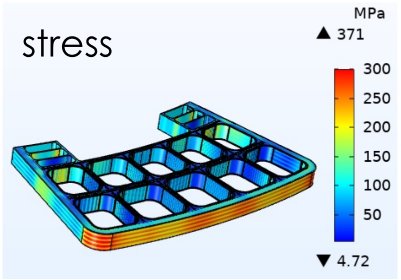
- **Pulsed operation not trivial for engineering aspects**
  - First Wall/Blanket/Vacuum Vessel/Magnets: many interfaces + extreme thermal and irradiation gradients
    - Cyclic stress - Have to survive thermal expansion/contraction
    - Material fatigue - Materials properties vary with temperature, irradiation



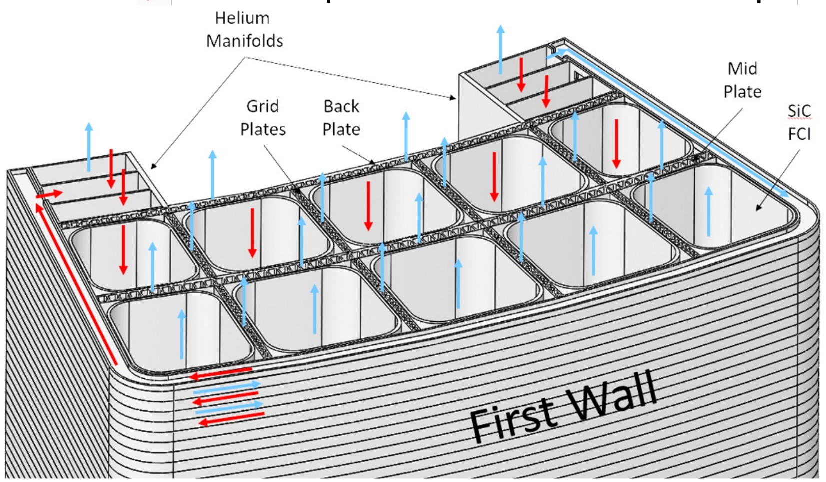
Tungsten temp-dependent recrystallizing, cracking







example blanket concept



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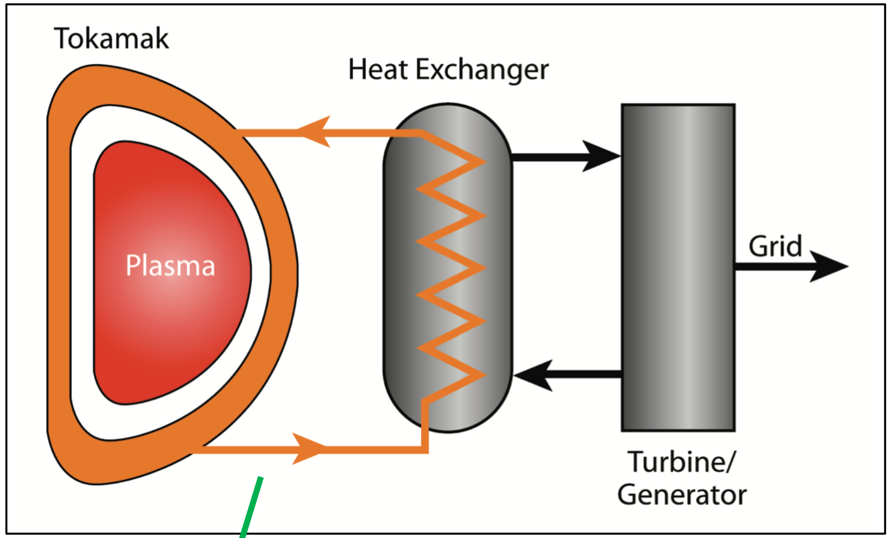
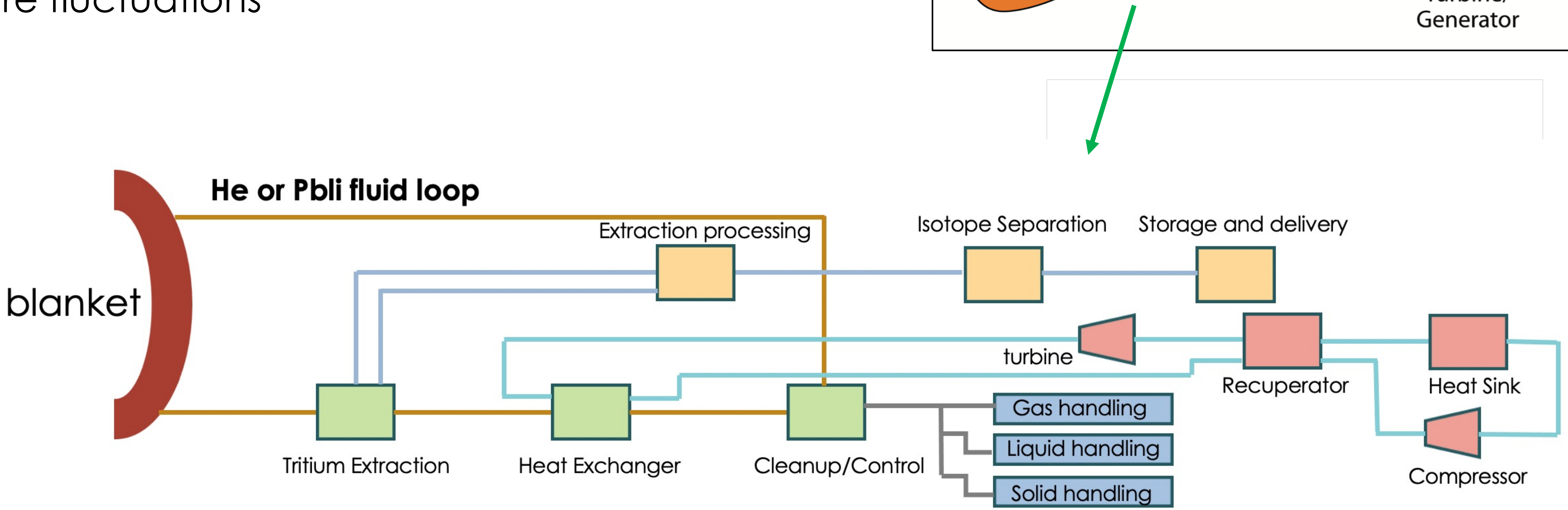
    - Material fatigue - Materials properties vary with temperature, irradiation
  - Thermal exchange systems cannot tolerate large temperature fluctuations





Example: Pulsed or Steady-State Tokamak?

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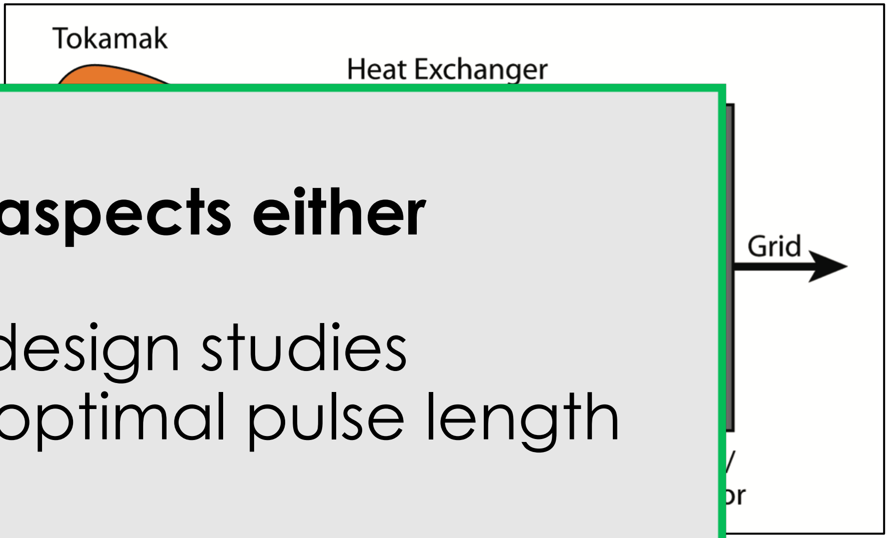
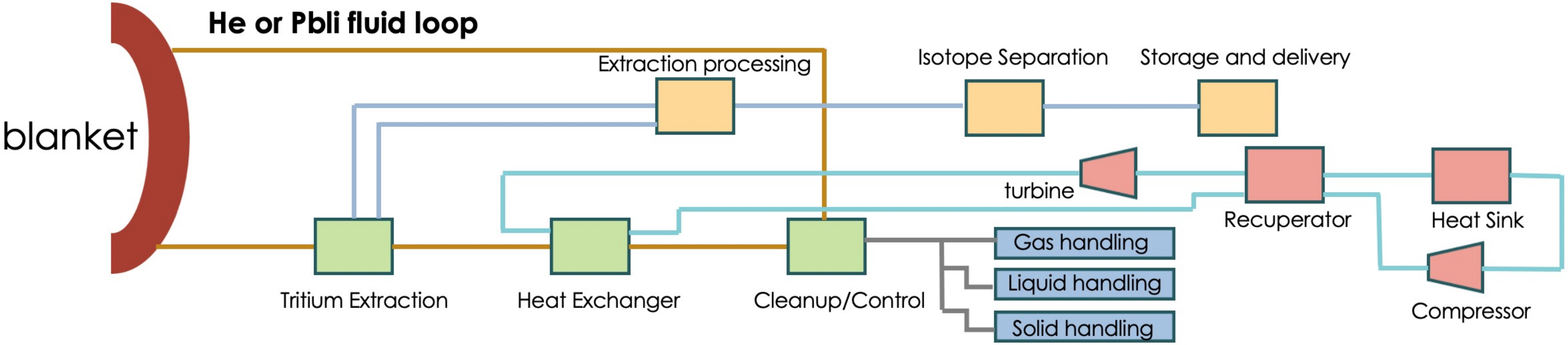
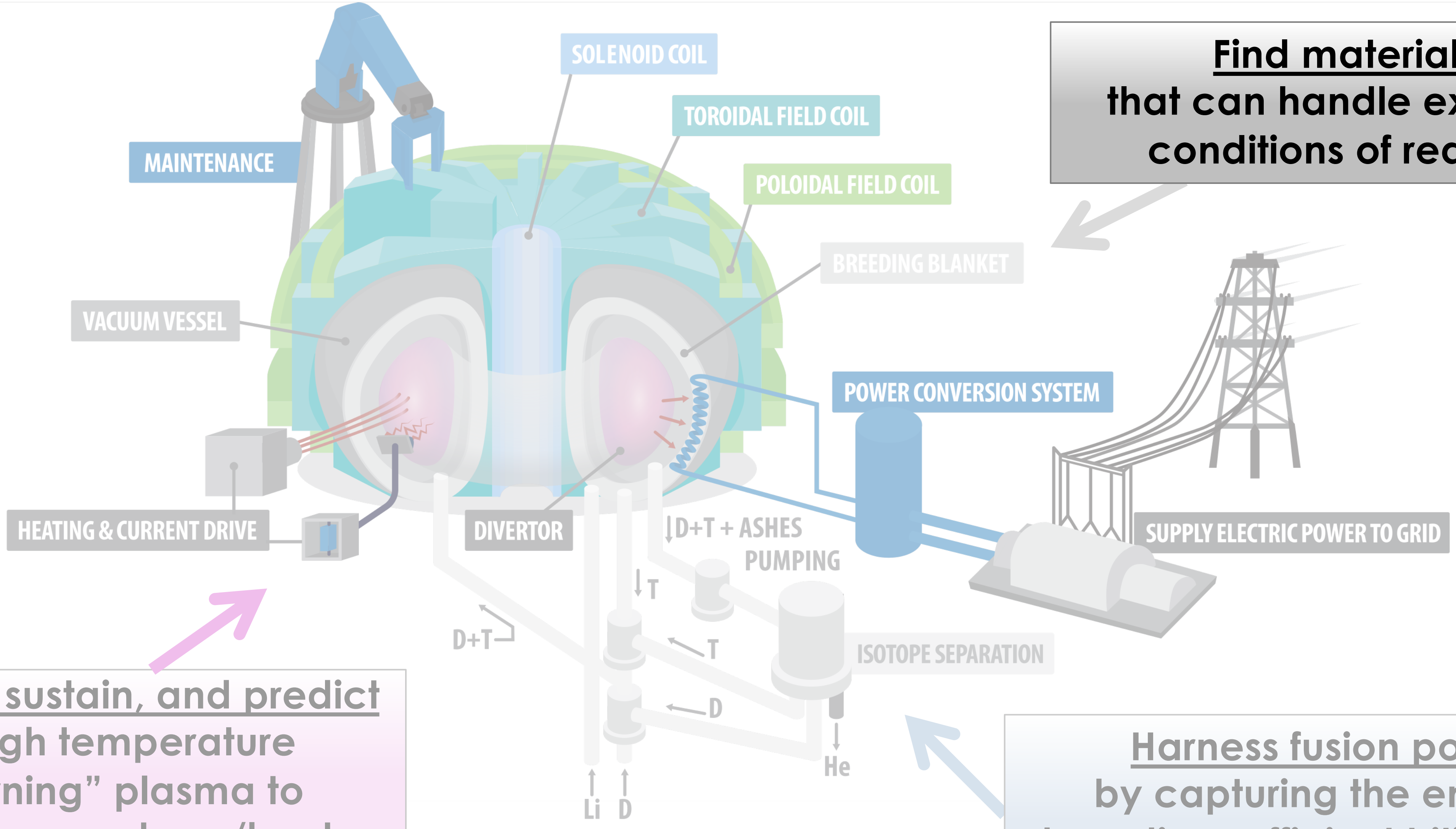


Pulsed operation not trivial for plasma aspects either

Ultimately, we need to do full system-design studies (plasma + engineering) to evaluate the true optimal pulse length (steady state vs. pulsed)



Generating Electricity from Fusion Energy Requires Meeting Three Scientific/Technological Challenges



Find materials that can handle extreme conditions of reactor

Control, sustain, and predict a high temperature "burning" plasma to produce neutrons/heat

Harness fusion power by capturing the energy, breeding sufficient tritium, and reliably producing net electricity

this was the easy part!

Material interactions are complex atomic + plasma processes

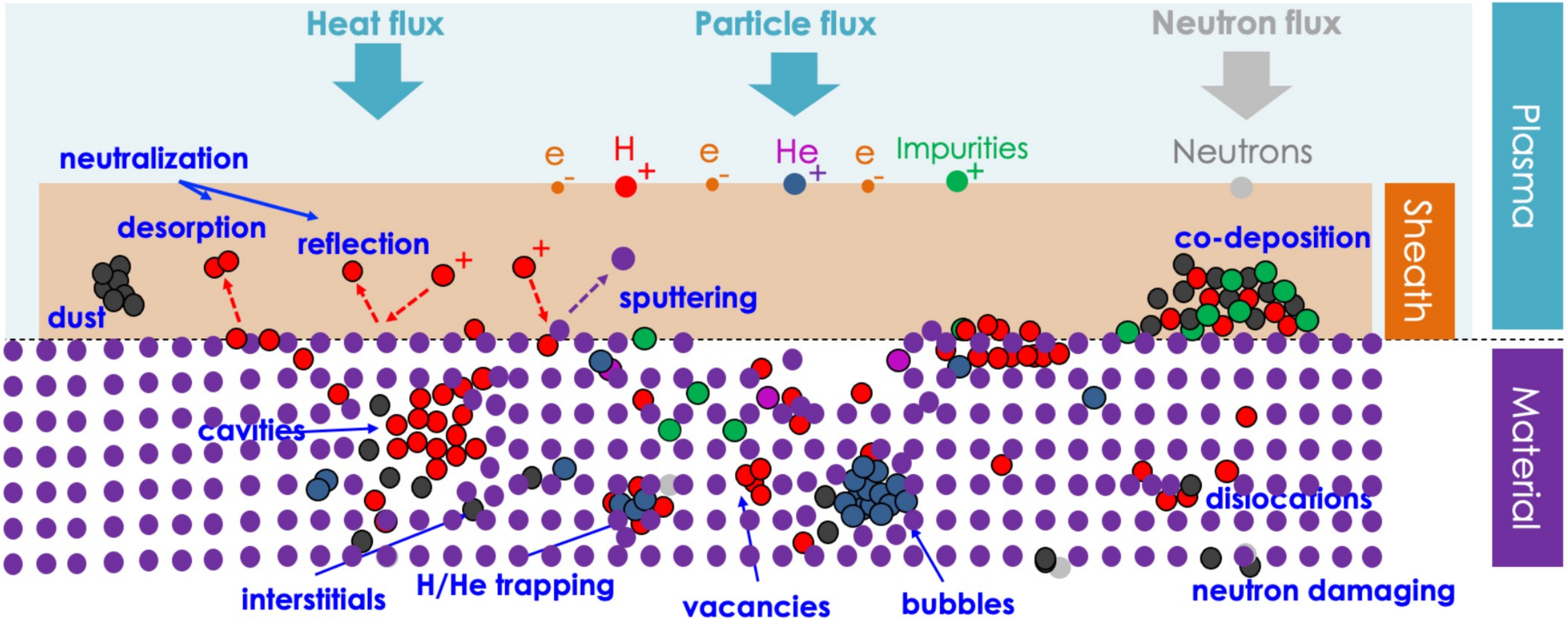
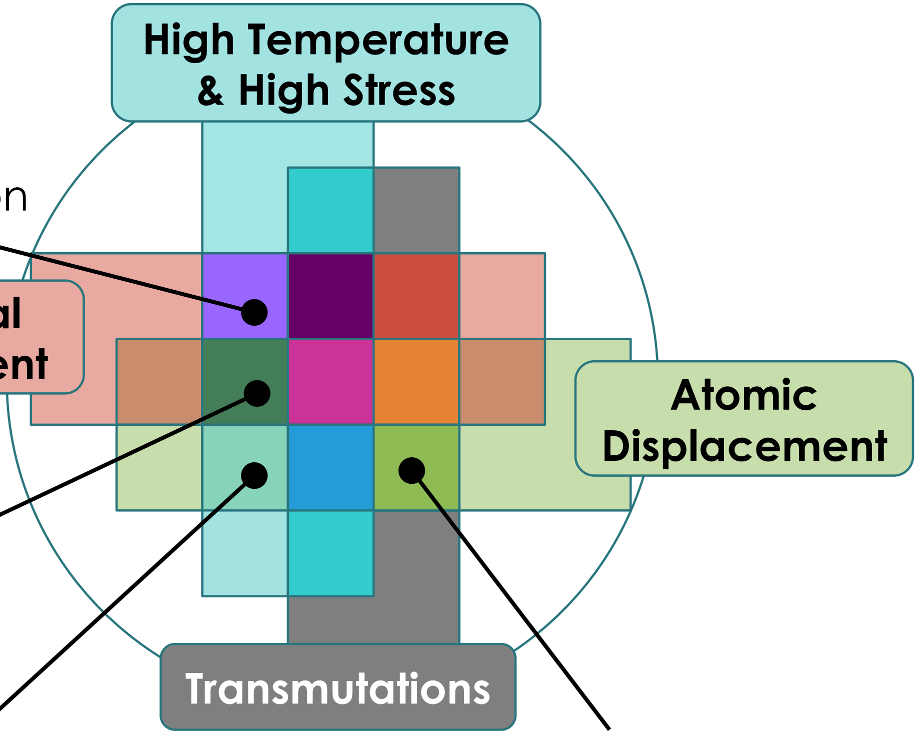


image credit: J. Guterl 2021 SULI

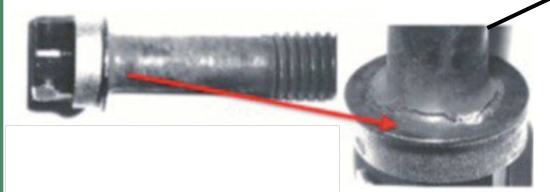
The frontier: incorporating materials data into design/assessment to say when and where failure might occur

Materials challenges span multiple-extremes

Stress-corrosion cracking

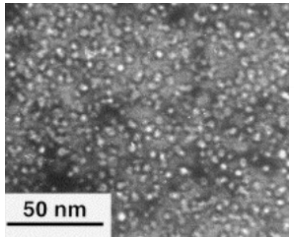


Irradiation-assisted stress-corrosion cracking



Irradiation-creep, fatigue, embrittlement

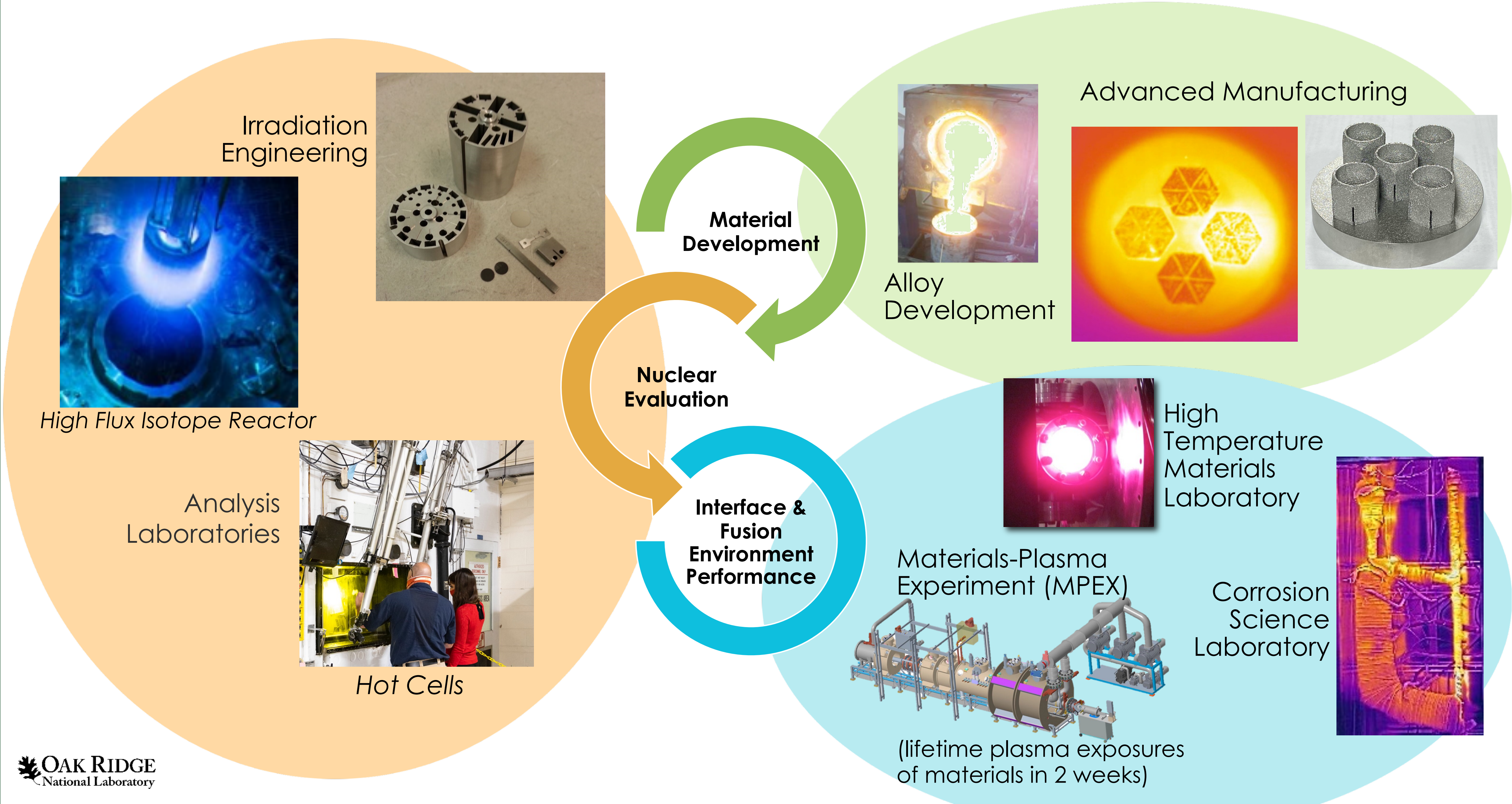
Helium-assisted cavity swelling



Ideal fusion-materials:

- Good for fusion plasma
  - won’t melt or degrade too quickly
  - won’t contaminate plasma
- Sustainable
  - low decay heat when activated by neutrons
  - reduced-activation to ensure waste is not long-lived
  - economical/scalable

The frontier: utilize national resources to develop fusion materials



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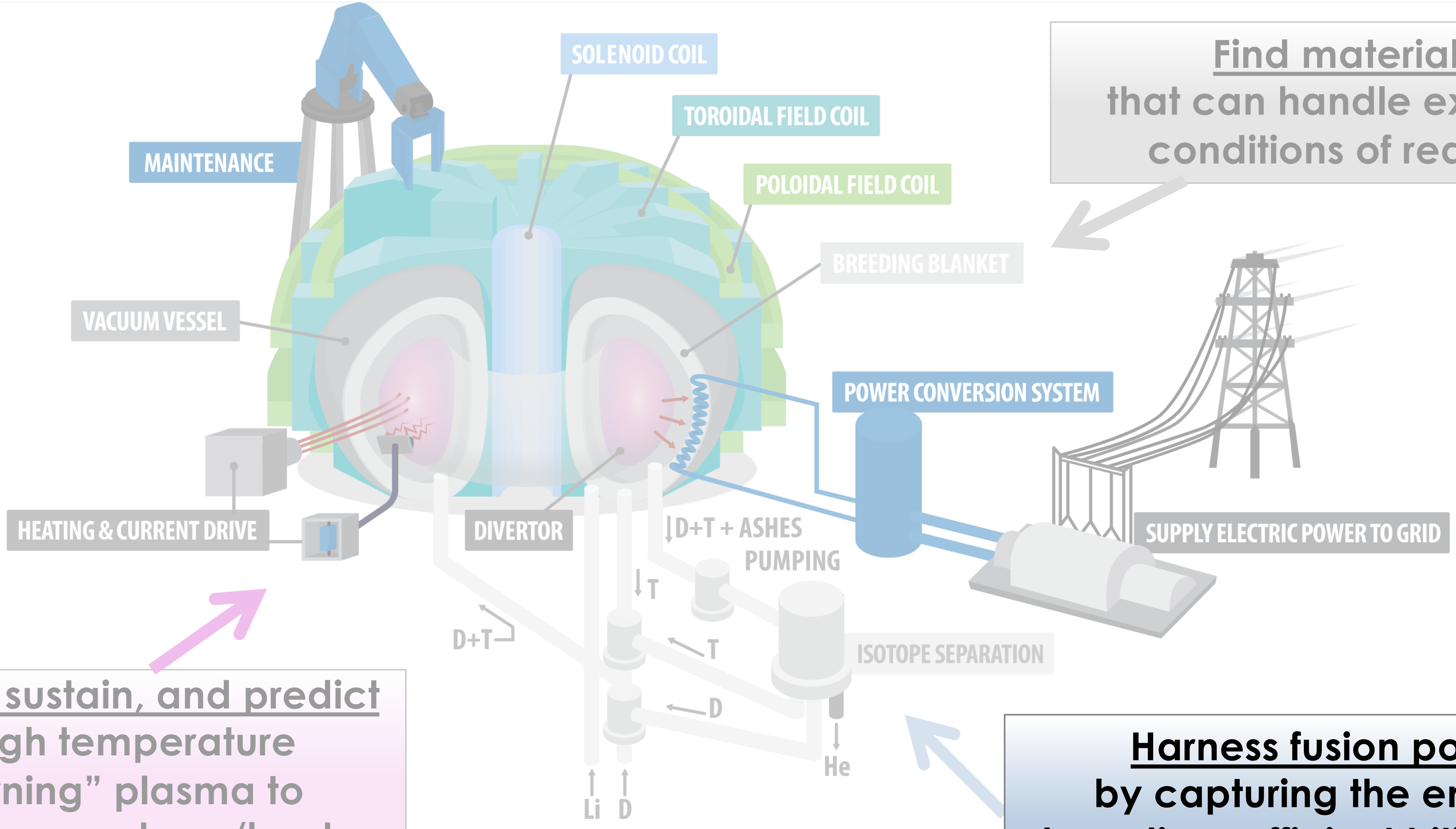

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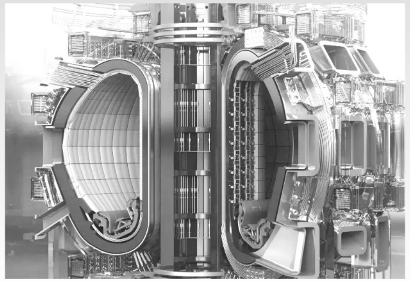
Control, sustain, and predict a high temperature "burning" plasma to produce neutrons/heat

Harness fusion power by capturing the energy, breeding sufficient tritium, and reliably producing net electricity

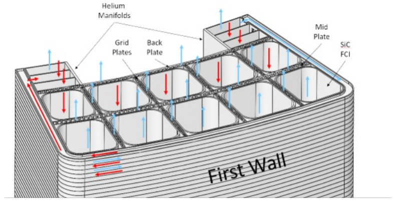
Examples of required (multi-discipline) blanket assessments

CAD	Neutronics

CAD



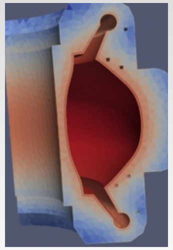
(full)

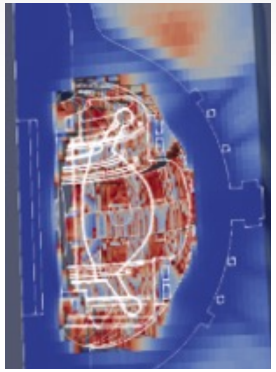


(sweep or slice)

Neutronics

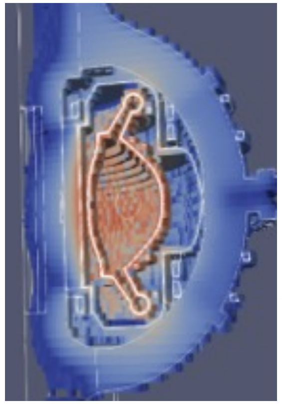
volumetric energy deposition





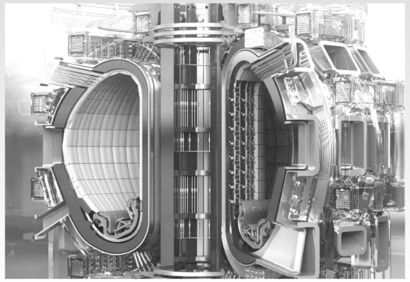
material activation, damage

shutdown dose rate



Examples of required (multi-discipline) blanket assessments

CAD



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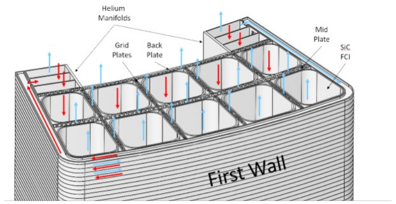
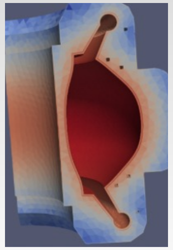
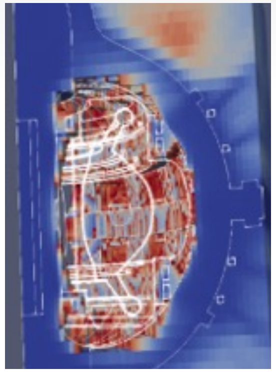


(sweep or slice)

Neutronics

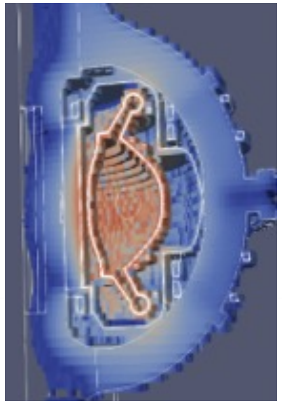
volumetric energy deposition





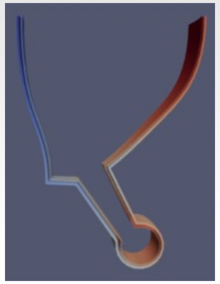
material activation, damage

shutdown dose rate



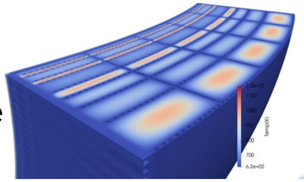
Thermo-mechanics

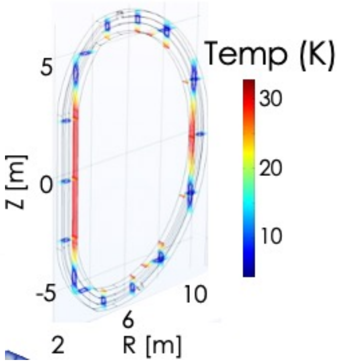
with irradiated property evolution



displacement

blanket temperature



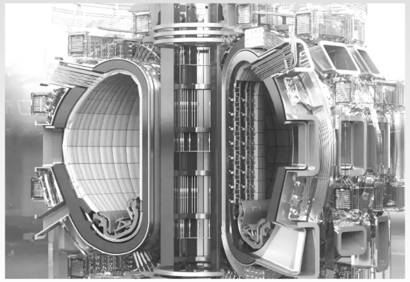


magnet heating

Examples of required (multi-discipline) blanket assessments

CAD	Neutronics	Thermo-mechanics	Thermal Hydraulics	Tritium Migration

CAD



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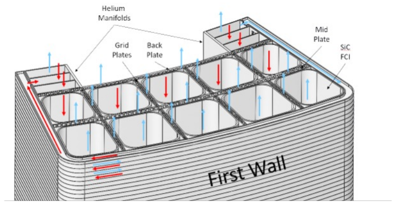
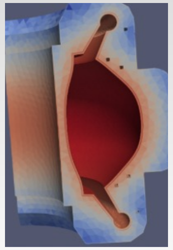
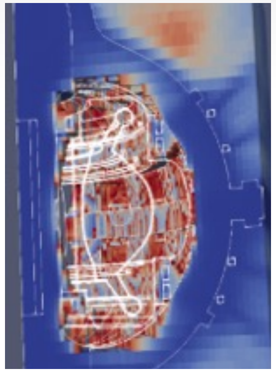


(sweep or slice)

Neutronics

volumetric energy deposition





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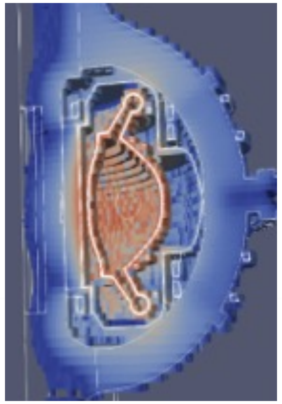

Thermo-mechanics

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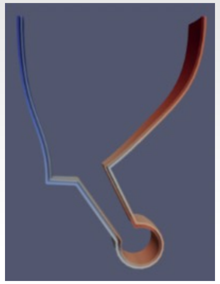
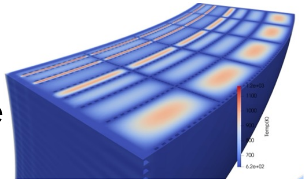
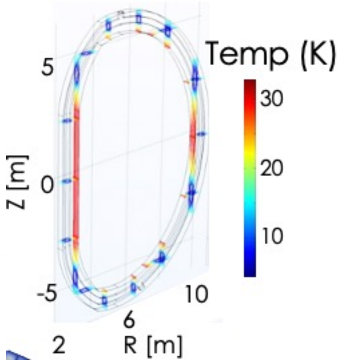


displacement

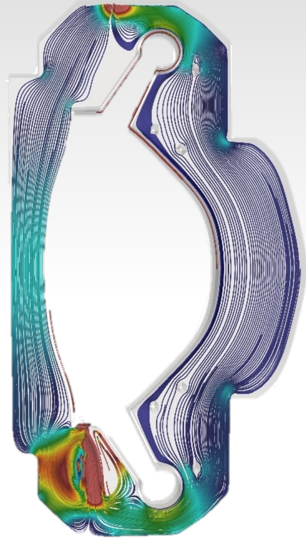
blanket temperature





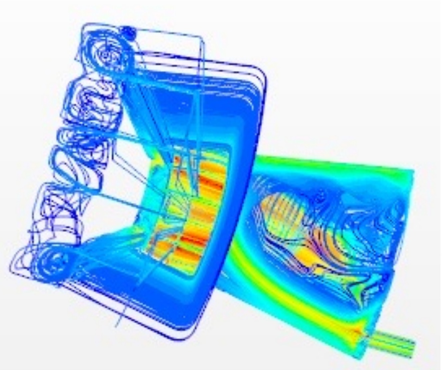
magnet heating

Thermal Hydraulics



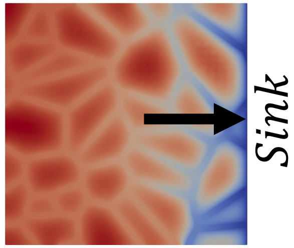
liquid metal CFD

Helium CFD



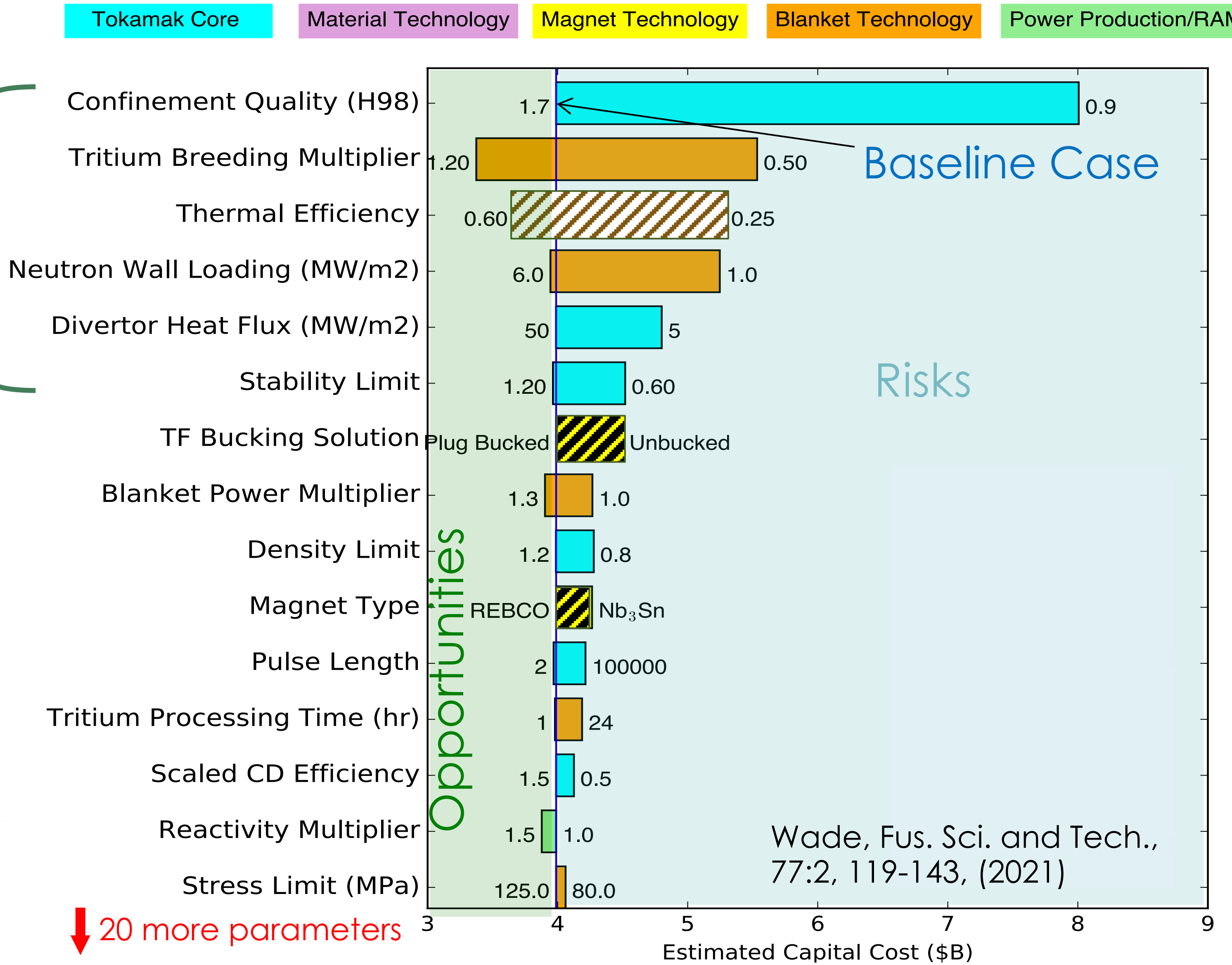
Tritium Migration

Tritium in ceramic breeder grains



Technology Advances Are Critical to the Delivery of Cost-Attractive Fusion Energy

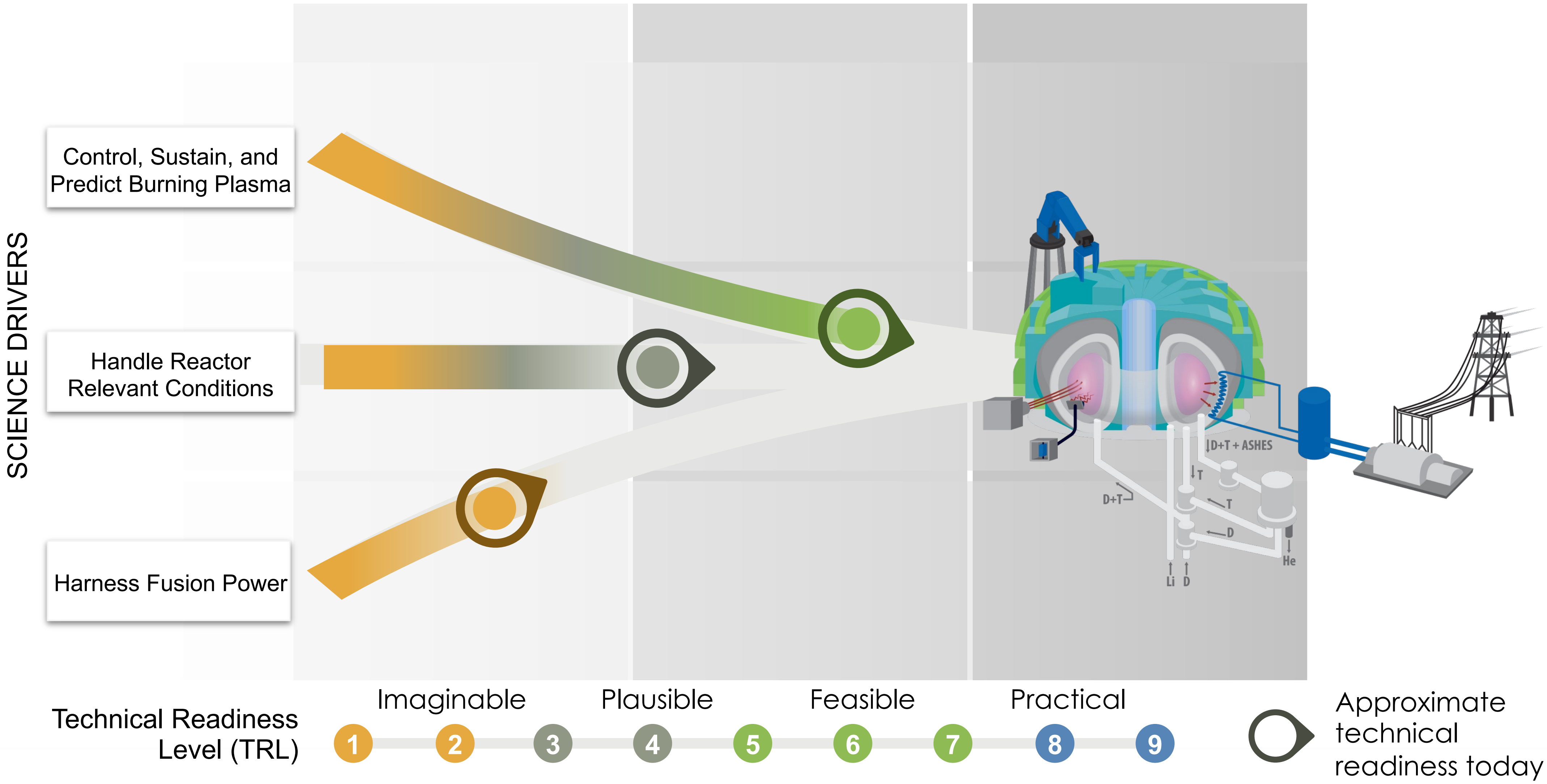
- Cost sensitivity analysis for fusion power plant identifies risk/reward of potential R&D (or lack thereof)
- **Critical R&D**
  - Plasma : core + edge solution
  - Blankets: thermal exchange, shielding, tritium breeding…
  - Materials: nuclear & interfaces, characterization, irradiation, corrosion, heat flux, advanced manufacturing …



Outline

- Motivation for magnetic fusion energy
- Challenges and frontiers in developing fusion energy
  - Burning plasma and fast-ion physics (focusing on tokamak)
  - Handling reactor conditions
  - Capturing the energy
- Progress in enabling more rapid fusion pilot plant design

Rapid progress is needed to reach a fusion pilot plant



Why is simulation needed for fusion reactor design?

- We NEED to build things, we have a wishlist
  - Remarkable progress has led to construction of net energy gain devices such as ITER and SPARC

    ...but these are still far from FPP regime (extrapolation required)
  - Rapid iteration takes time & money & people

    ...still waiting for new facilities from FESAC

Portfolio Elements	Scenarios		
	Constant	Modest Growth	Unconstrained
New Construction of Midscale+ Facilities			
✅ MPEX	Yes	Yes	Yes
FPNS	Yes, but highly delayed	Yes, but delayed	Yes
EXCITE	No	Yes, but highly delayed	Yes
Mid-Scale Stellarator	No	No	Yes
BCTF	No	No	Yes
HHF-Component	No	No	Yes

- Simulations can save time
  - Catch issues with integration (to succeed when building/testing full systems)
  - Guide design decisions (de-risk options with physics-based prediction and uncertainty)
  - Expedite innovative solutions (freedom to experiment in a virtual testbed)

- Simulations are needed for safety, economics/scalability
  - Many concepts will need evaluation of shielding, tritium management, materials activation and lifetimes *before you build*

The Fusion REactor Design and Assessment (FREDA) Project aims to speed reliable fusion power plant design

FREDA

- *FREDA is a new 4-year SciDAC project;*
  - *Oak Ridge National Laboratory (lead)*
  - *Lawrence Livermore National Laboratory*
  - *Sandia National Laboratories*
  - *General Atomics*
  - *University of California San Diego*
- *Mission*: Develop an unprecedented capability to perform routine, multi-fidelity, self-consistent integrated assessment of the fusion-plasma and the required fusion-engineering components.

SciDAC
Scientific Discovery through Advanced Computing

The ability to perform rapid *integrated* assessment and iteration before proceeding to detailed reactor design is a fundamental rate limiter

Traditional Fusion Reactor Design Studies

multi-physics

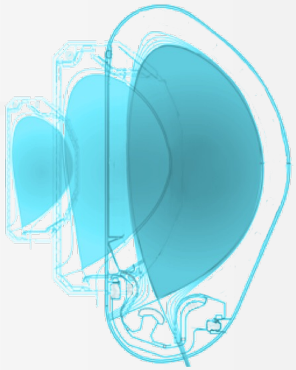
SCIENCE DRIVERS

Control, Sustain, and Predict Burning Plasma

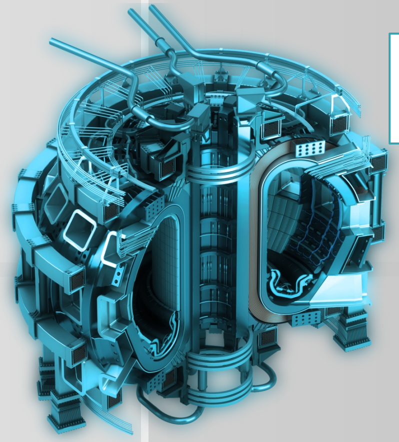
Handle Reactor Relevant Conditions

Harness Fusion Power

1. Systems code couples large set of simplified plasma + engineering relations to find target design point



2. Humans spend time drawing geometry/CAD



3. Feasibility is checked with complex high-fidelity simulations

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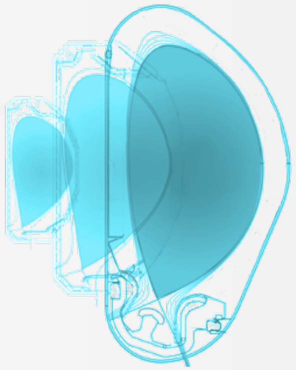

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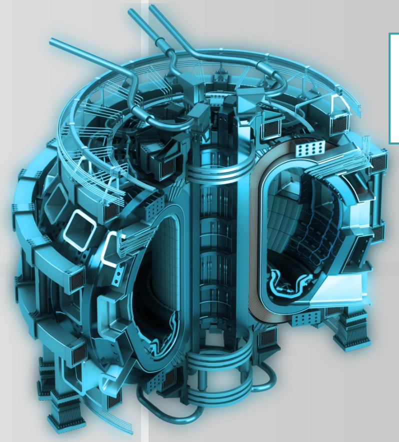
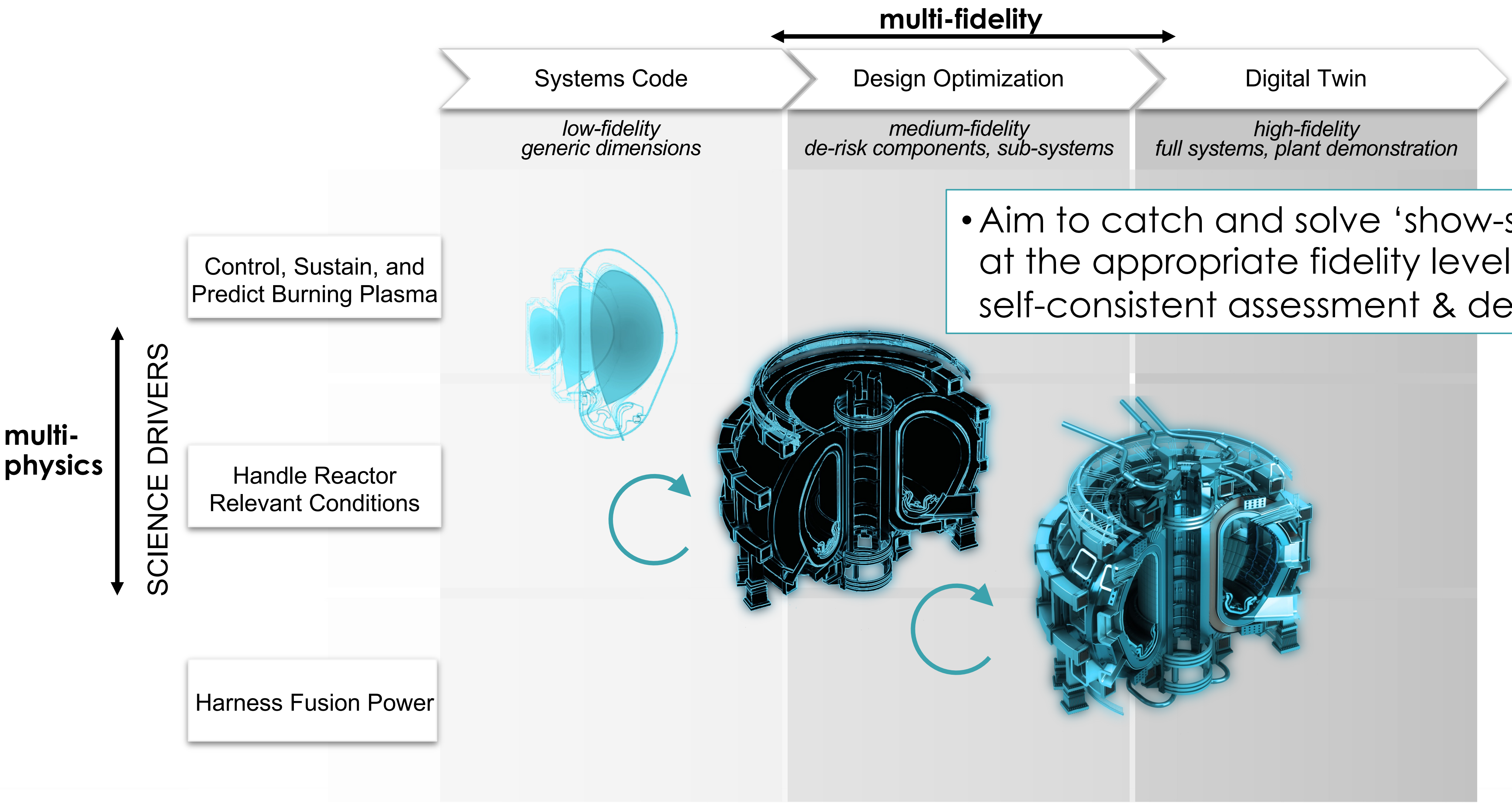


3. Feasibility is checked with complex high-fidelity simulations

- Issue: **Empirical scaling misses connections** between plasma (e.g. actual profiles) and the machine design →design point not necessarily feasible or optimum

FREDA is a purpose-built framework for multi-fidelity, iterative optimization

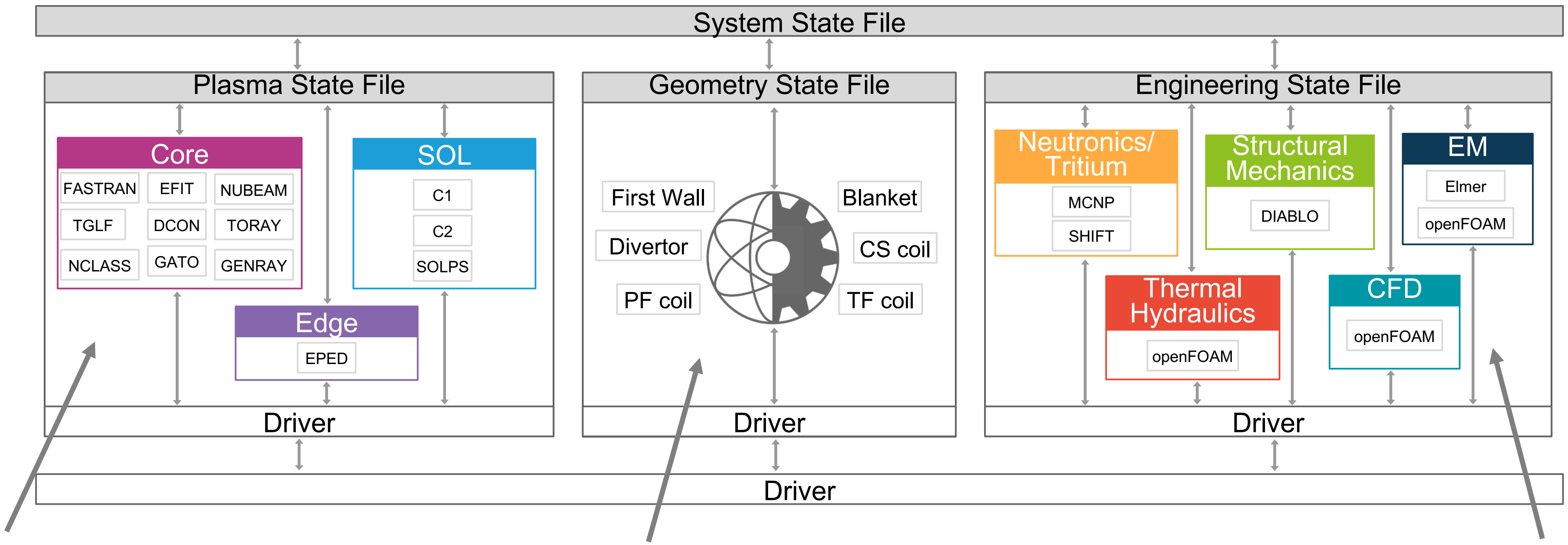


- Aim to catch and solve 'show-stoppers' at the appropriate fidelity level using self-consistent assessment & design optimization

Approach: flexible component-based framework & data structure

Framework & Workflow

Capable of integrating swappable modules with diverse CPU/GPU requirements



Fusion-Plasma

- Based on the open-source IPS (Integrated Plasma Simulator) developed in AToM SciDAC

(developed over a decade)

Parametric Geometry

- Includes systems codes and parameterized geometry representation

(used in ARIES, ACT fusion reactor studies)

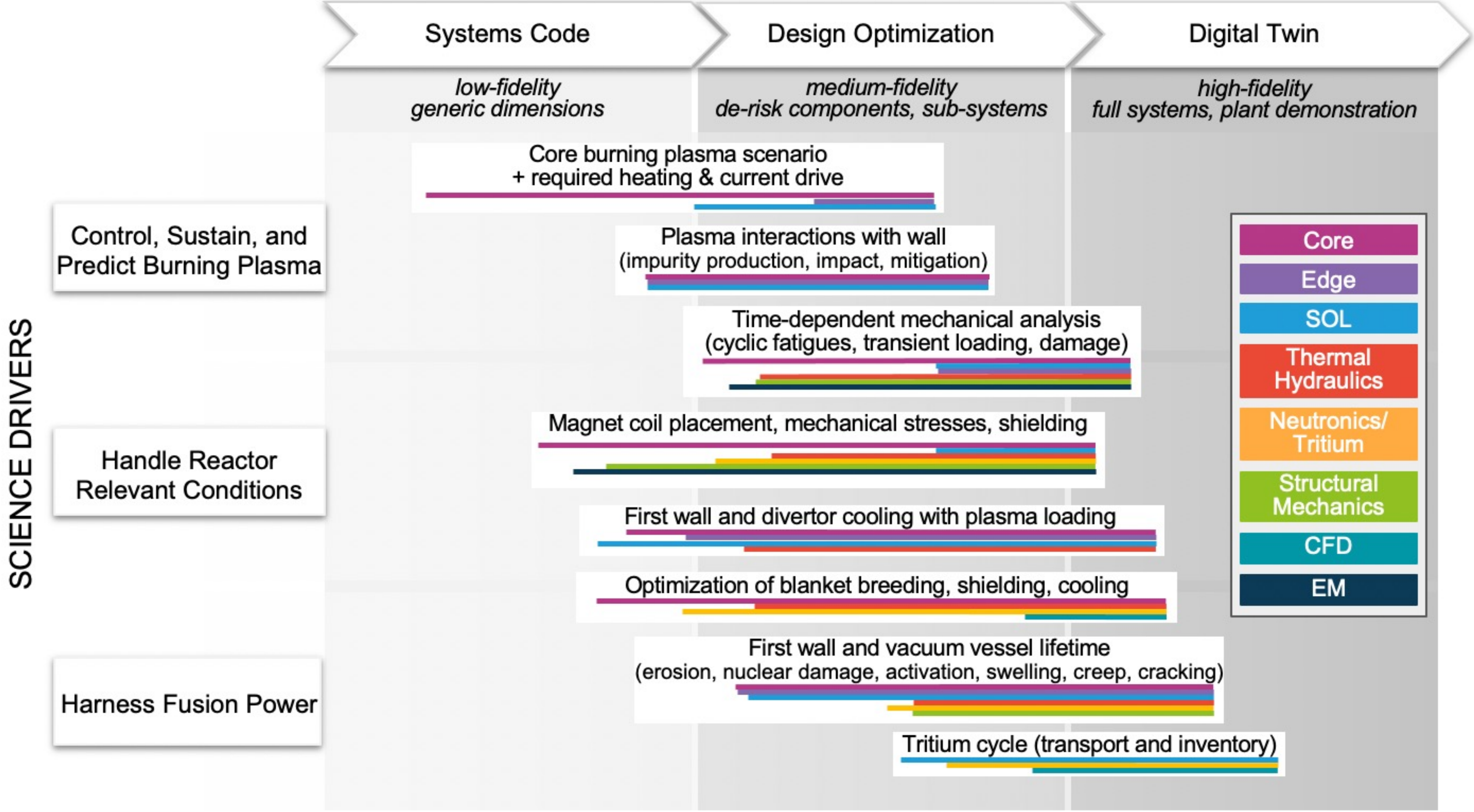
Fusion-Engineering

- Includes multiphysics simulation tools based on Fusion Energy Reactor Models Integrator (FERMI)

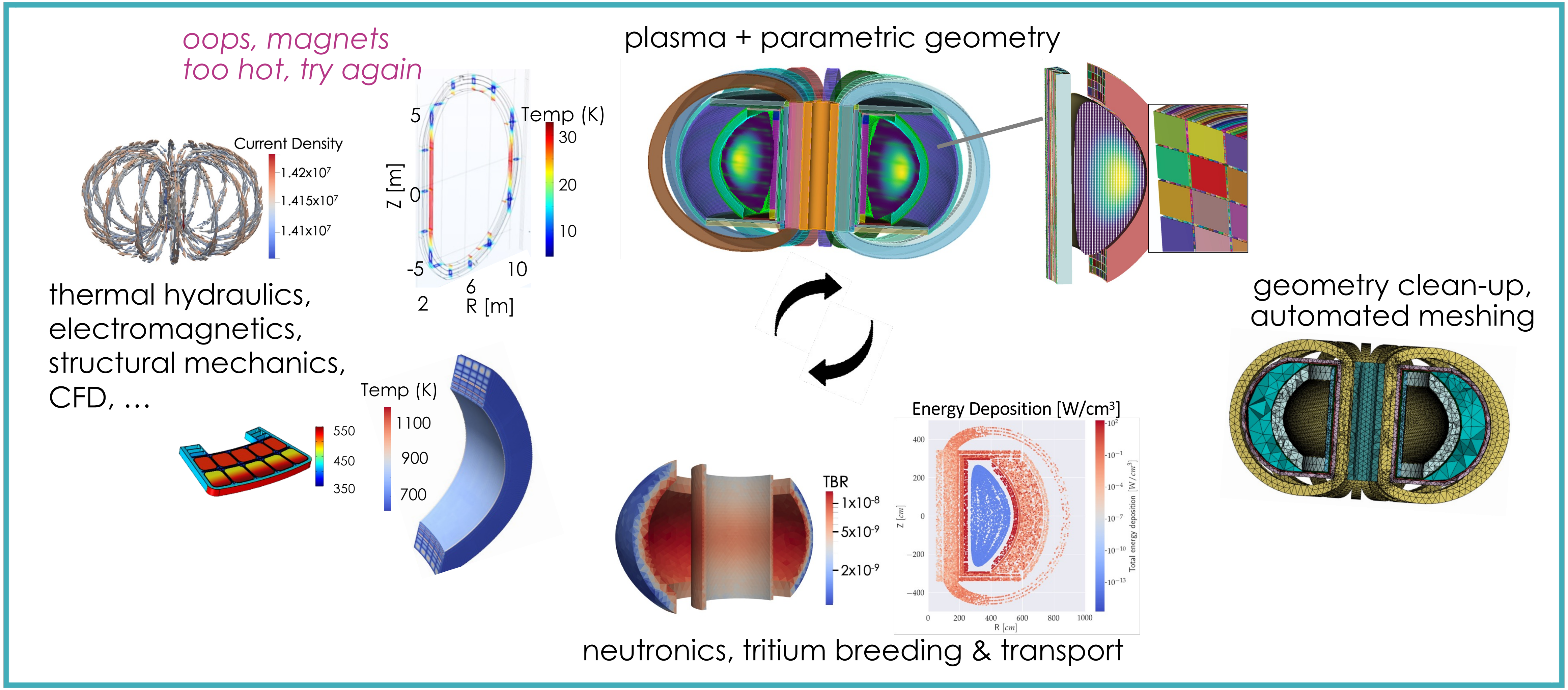
(developed in past 3 years)

FREDA will focus on key tokamak challenge problems

…expecting that the capability developed will apply to other concepts



FREDA will help us see how each of the physics/engineering components and uncertainties impacts the full system

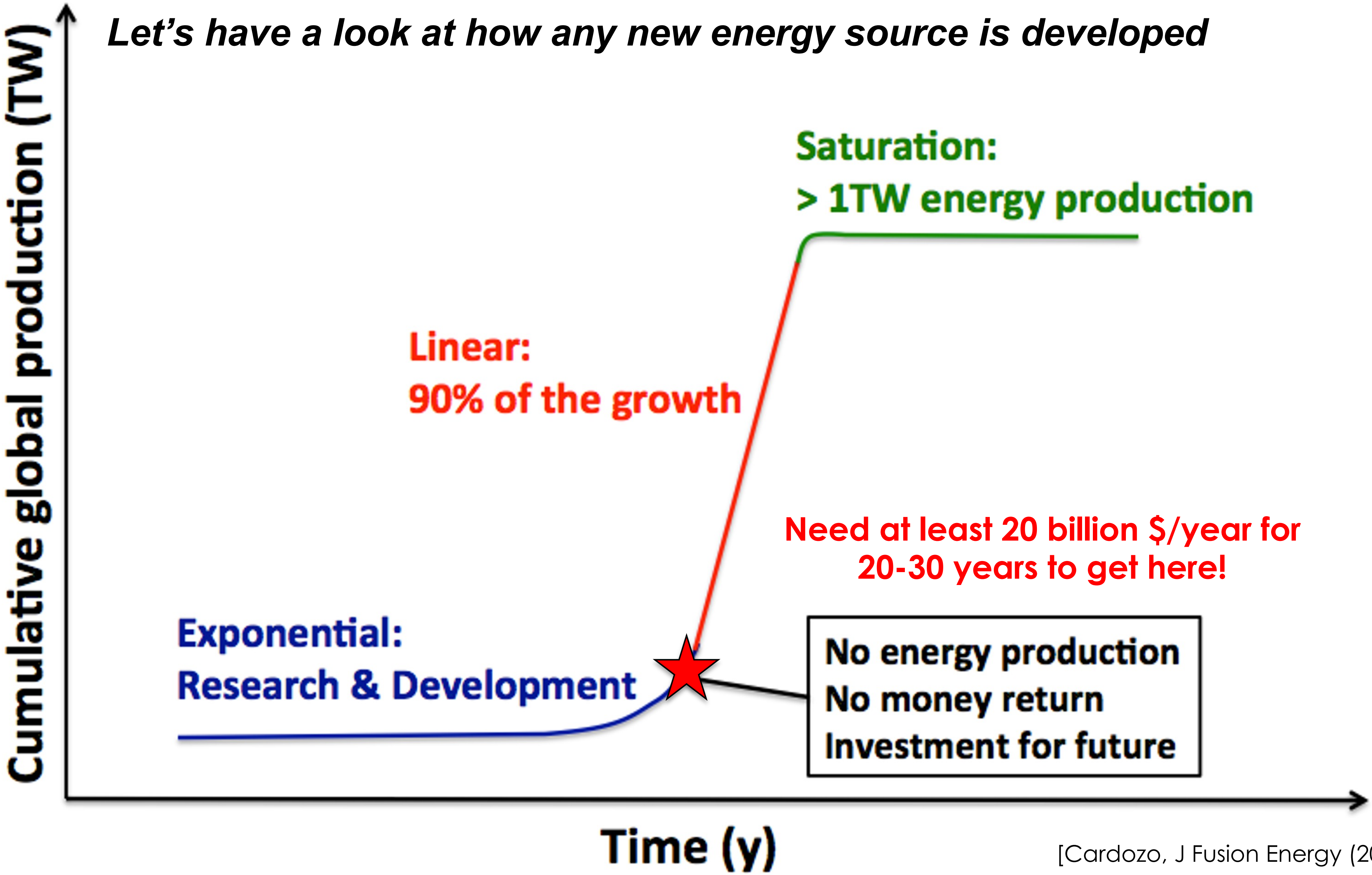


Even if predictions for an FPP regime are not yet validated, this ability allows progress in assessing feasibility of engineering requirements and tolerances.

“Creating a Sun on Earth” is a Grand Challenge for the 21st Century

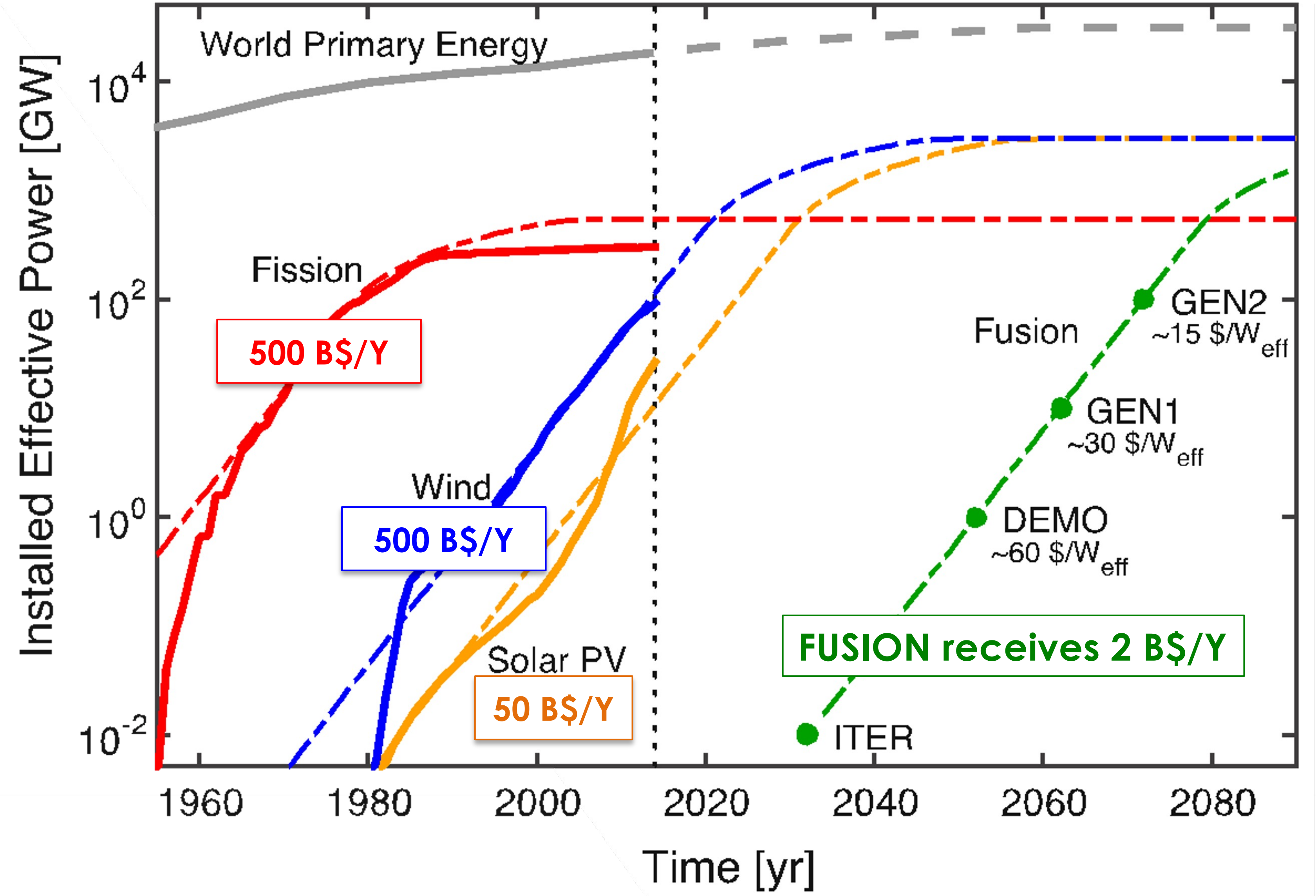
National Academy of Engineering listed Fusion Energy among 14 Grand Challenges for Engineering in the 21st Century

Why is Fusion Taking So Long to Achieve?



[Cardozo, J Fusion Energy (2016) 35:94–101]

World Investment Needed to Reach EXPONENTIAL GROWTH Phase of Energy Sources



[Cardozo, J Fusion Energy (2016) 35:94–101]

Closing Thoughts

- **There are many challenges in fusion reactor design**
  - Probably makes your head spin →
  - But great job security/career option

- **Our best plasma+engineering modeling tools need to be utilized and integrated to make progress faster**

- **ORNL is committed to fusion pilot plant success, addressing key issues with the most leverage on performance and cost**
  - join us! www.ornl.gov/division/fed

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