PPPL PRINCETON PLASMA PHYSICS LABORATORY

The emerging role of public-private partnerships in fusion energy R&D … and my evolving career

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APS March meeting

March 8, 2023

Why am I up here talking about fusion energy… and industry?

- **To share recent progress and opportunities**
  - Recent milestones in fusion gain and technology achievements
  - Significant growth of investment-backed fusion industry companies aggressively pursuing commercialization
  - Support from White House, congress, and DOE to expand R&D and move quickly

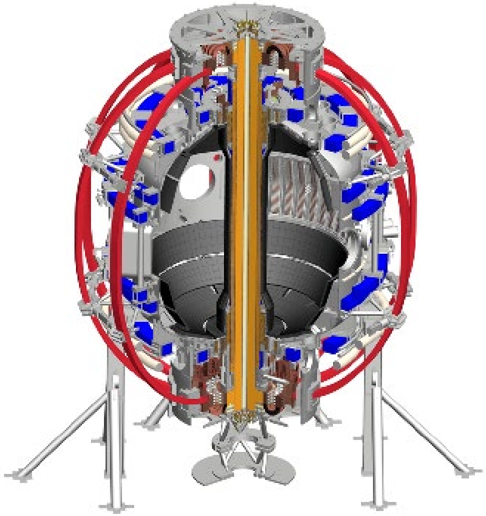
- **To share a bit about my career trajectory**
  - Non-traditional path to doing physics research I love
  - I've become a believer that commercial fusion energy is a possibility and I want to make a more direct, immediate impact

What do I currently do?

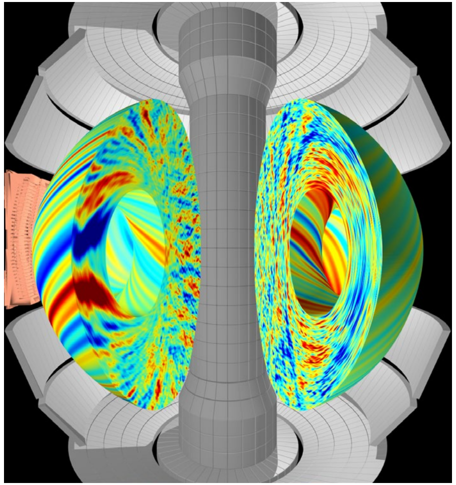
My current professional roles: research

NSTX-U Research (PPPL)

Physicist



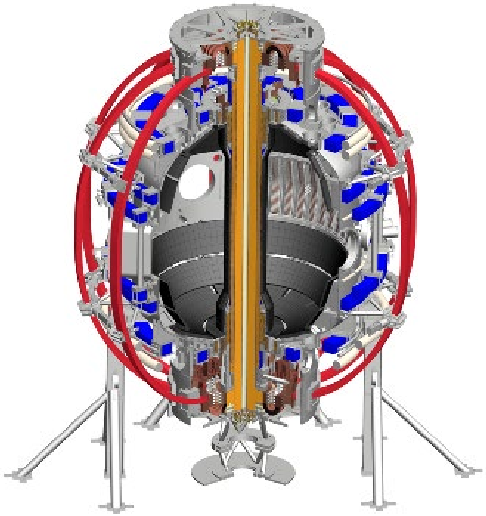
Tokamak **fusion** experiment studying steady-state, high-confinement scenarios



Validation and prediction of turbulent energy losses that determine fusion gain in magnetized plasmas

My current professional roles: research & management

NSTX-U Research (PPPL) (75%)
Deputy Director & Physicist



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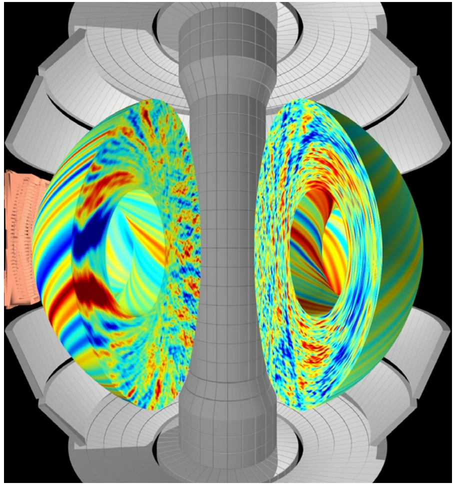
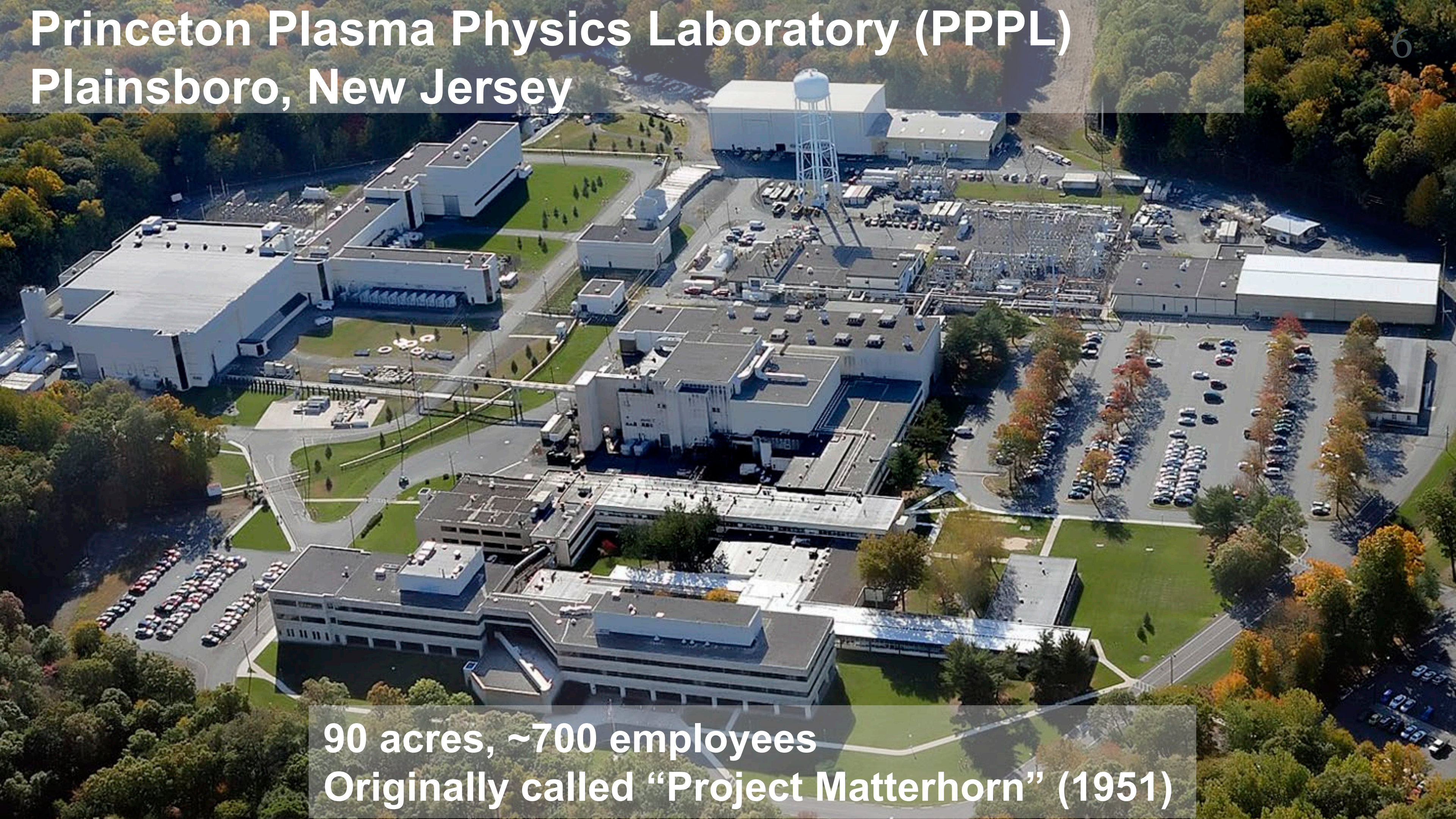


Validation and prediction of turbulent energy losses that determine fusion gain in magnetized plasmas

INFUSE Program (25%)
Deputy Director

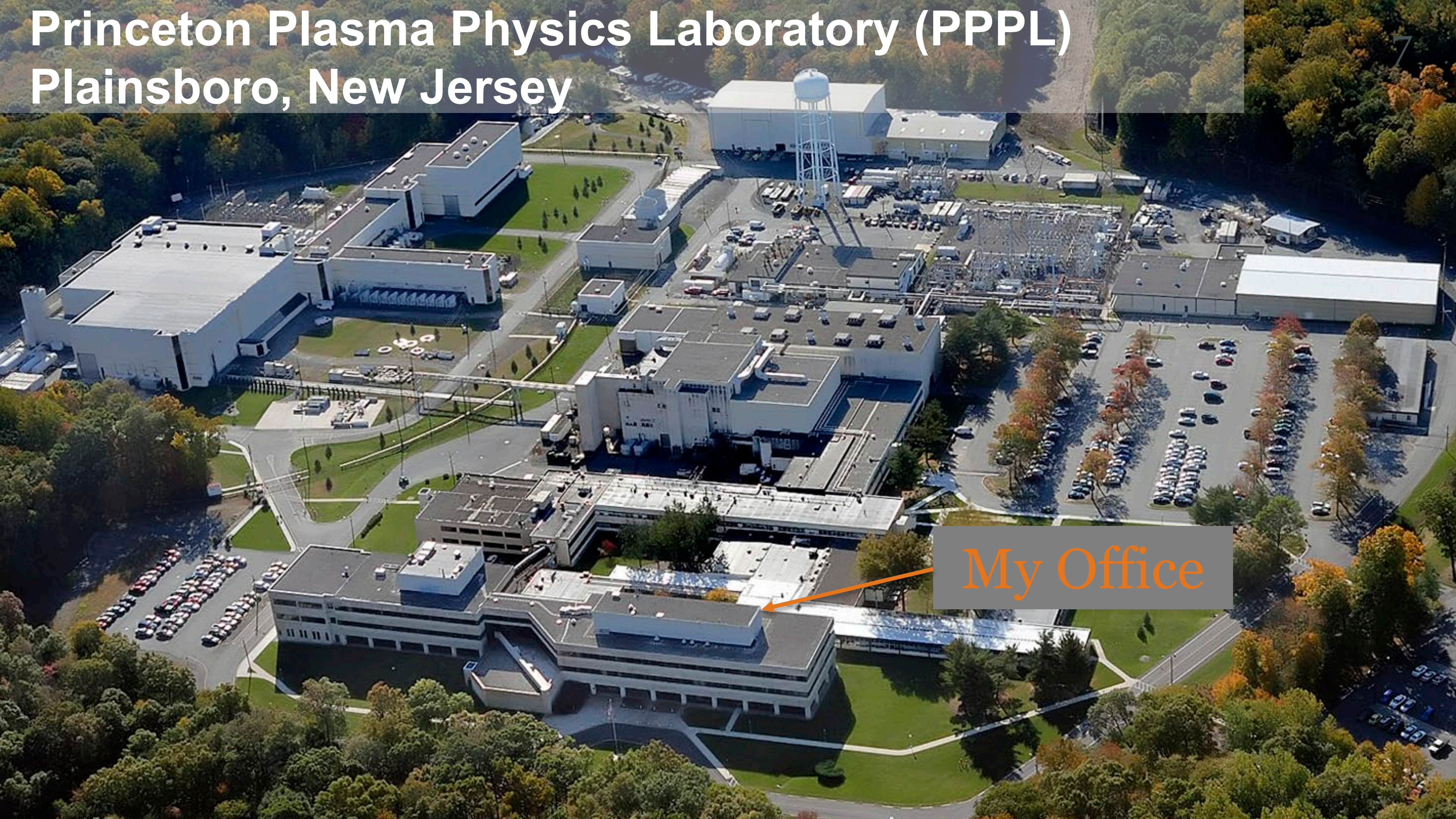
Public-private partnership cost-share program to support the growing **fusion industry**

Princeton Plasma Physics Laboratory (PPPL)
Plainsboro, New Jersey

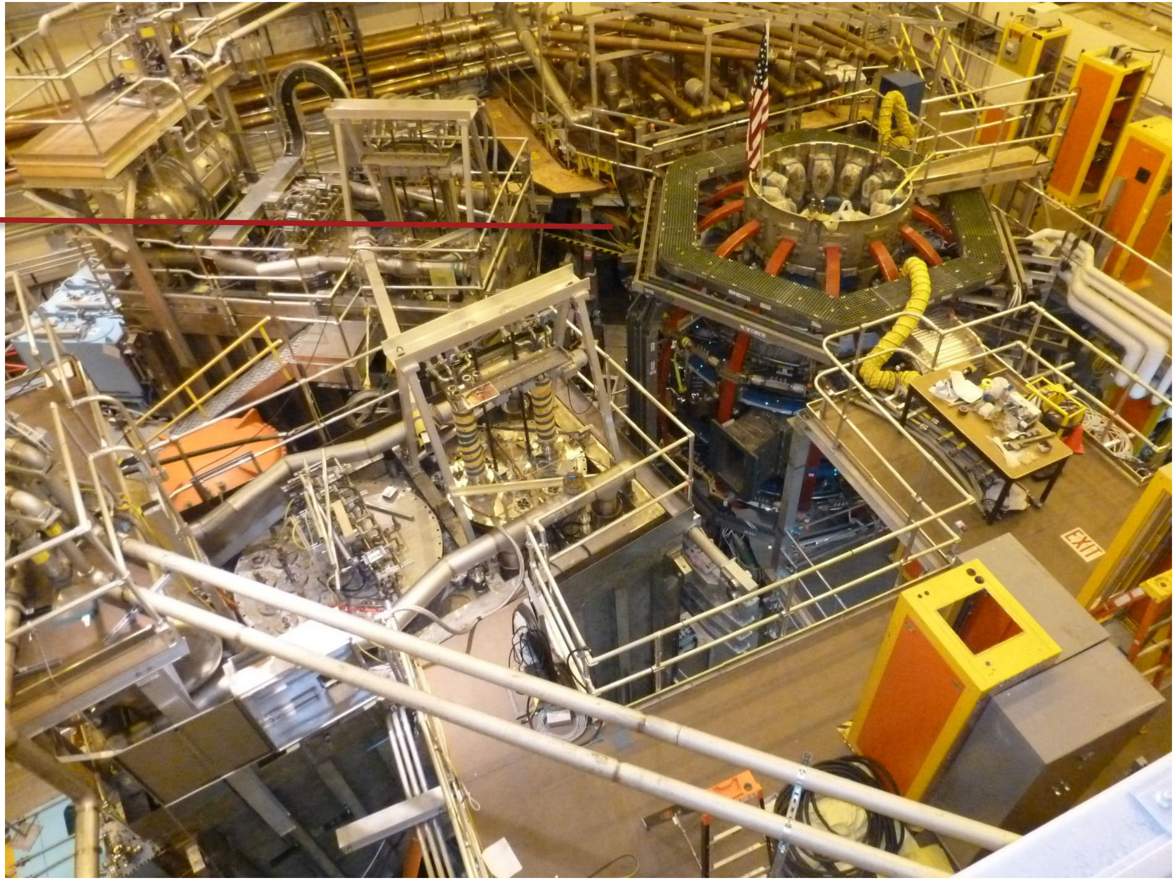


90 acres, ~700 employees
Originally called "Project Matterhorn" (1951)

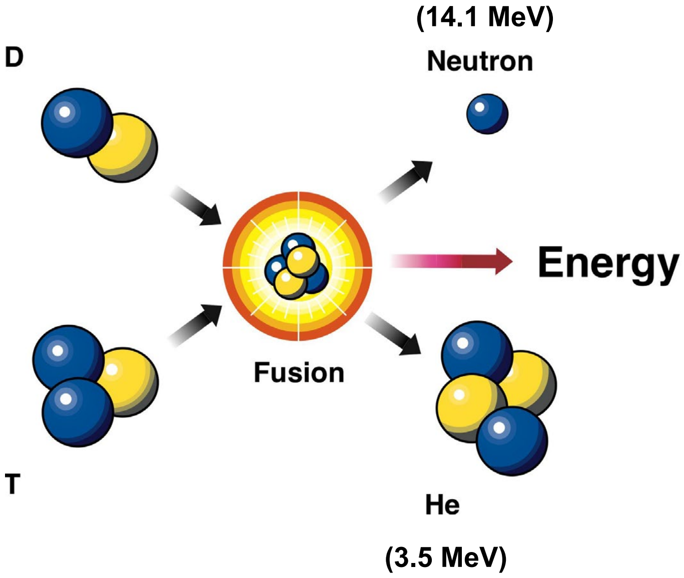
Princeton Plasma Physics Laboratory (PPPL)
Plainsboro, New Jersey



National Spherical Torus Experiment – Upgrade (NSTX-U)



Fusion basics and recent progress



$$
\begin{array}{ll}
 & D + T \rightarrow {}^{4}He + n + 17.6\ MeV \\
+ & Li + n \rightarrow {}^{4}He + T + 2.3\ MeV \\
\hline
\approx & \mathbf{D + Li \rightarrow 2\ {}^{4}He + 20.0\ MeV}
\end{array}
$$

Promises of fusion for carbon-free energy

- No carbon emission
- Fuel (D, Li) is abundant
- No melt down/runaway concerns (grams of fuel in the device)
- Mostly low-level radioactive waste
- Expected to be continuous/baseload, complementary to intermittent renewables

Disadvantages

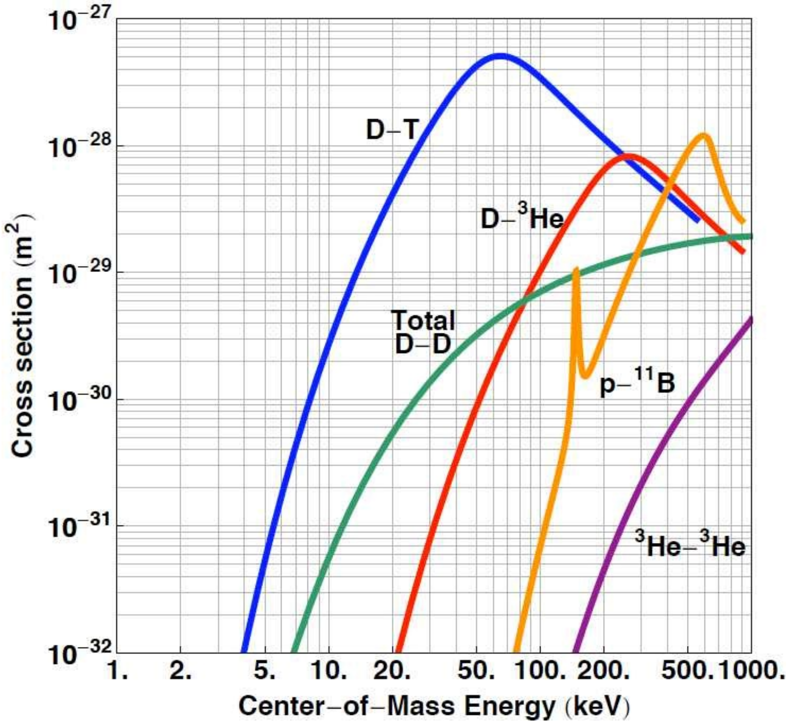
- Challenge to obtain confinement of ~15M °C plasma
- Materials challenges from high plasma heat flux (10's MW/m^2) and 14.1 MeV neutron irradiation
- Volume of low-level waste may be high
- D-T fusion requires tritium breeding, handling, processing
- Licensing challenges

(*How will this ever be economically competitive!*)

Thermonuclear D-T fusion requires high temperature plasma

For thermonuclear DT fusion, require T~10-15 keV (100-150M °C)

$$P_{fusion} \sim (nT)^2 \cdot \text{Volume}$$



Fusion “science” gain depends on the triple product (Lawson criterion)

“0D” steady-state power balance

Energy confinement time quantifies rate of losses → $\frac{W}{\tau_E} = P_{loss}$

$$\frac{nT \cdot V}{\tau_E} \sim (nT)^2 \cdot V + P_{external}$$

Fusion triple product

$$\mathbf{nT\tau_E \sim \frac{Q_p}{Q_p + 5}}$$

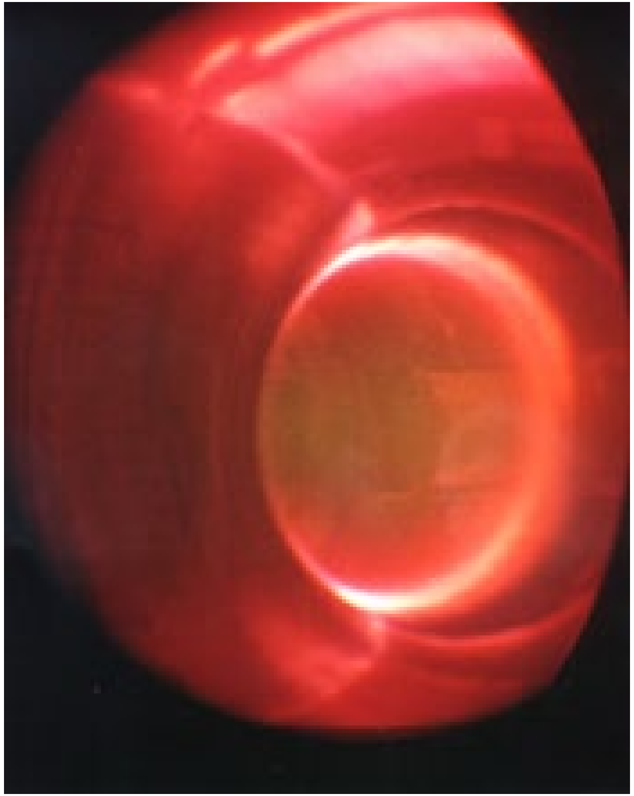
Fusion science gain

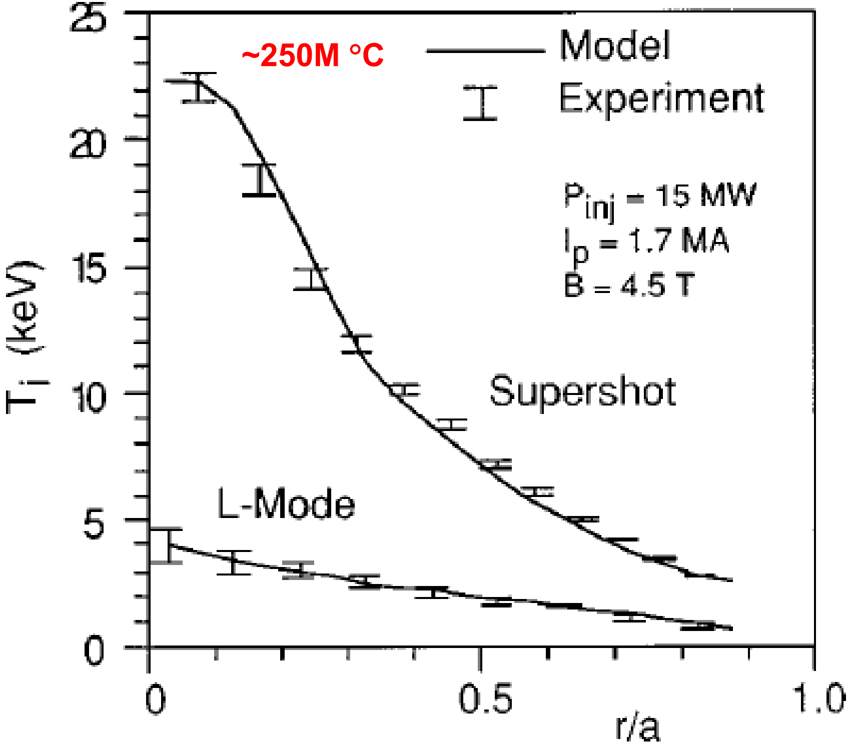
$$\mathbf{Q_p = \frac{P_{fusion}}{P_{external}}}$$

$nT\tau_E$ ~8 atm-sec for steady-state ignition ($Q_p \rightarrow \infty$)

Necessary temperatures achieved in the 1990's

Tokamak Fusion Test Reactor (TFTR at PPPL)





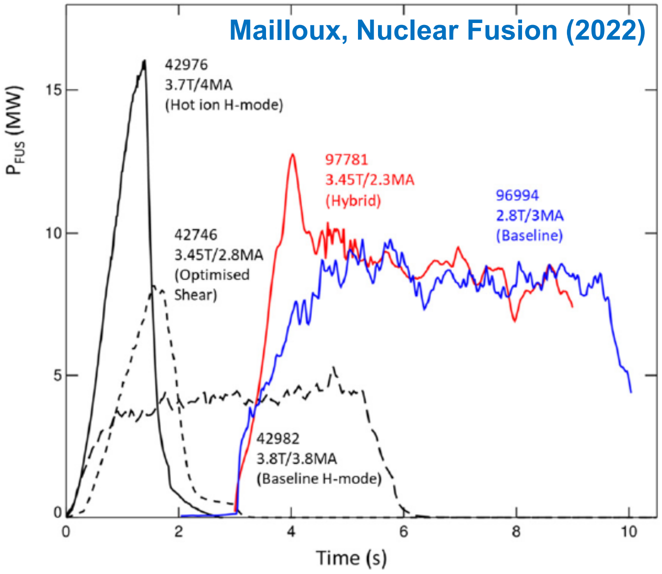
core

boundary

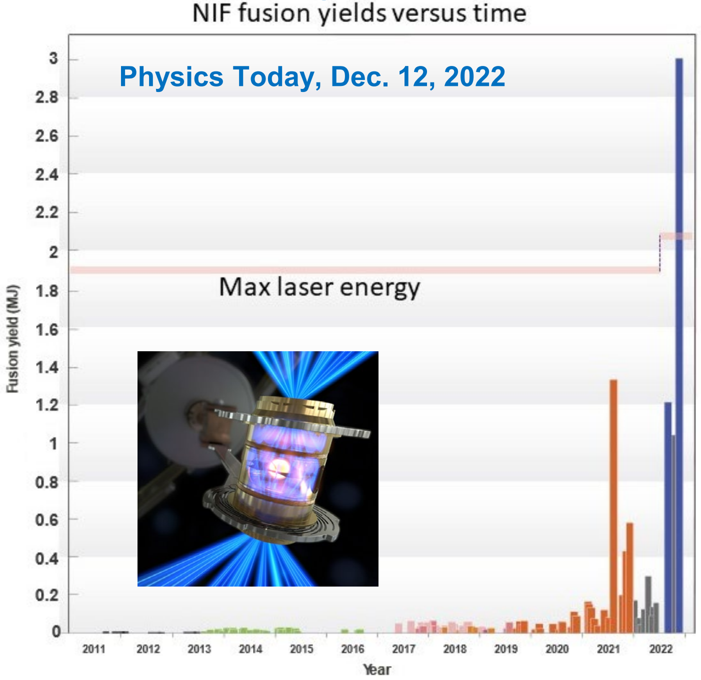
Significant performance milestones recently achieved

JET tokamak DT fusion (Feb. 2022) integrating reactor-relevant:

- Fusion performance: P_{fus}=8 MW (Q_p~0.25) for 5 secs
- Heat exhaust management with reactor-relevant plasma facing materials (Be, W)
- Control and mitigation of transient events
- Tritium processing

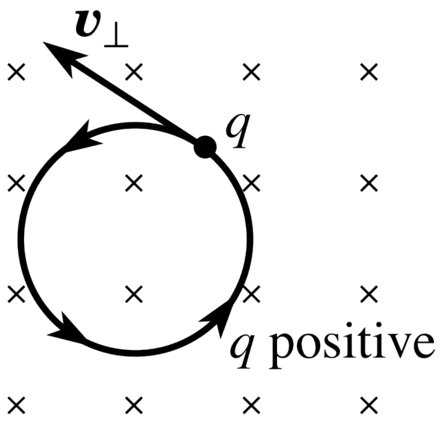


National Ignition Facility (LLNL) achieved DT ignition, scientific energy breakeven & ignition



Magnetic confinement fusion relies on … magnetic fields

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$



gyroradius: $\boldsymbol{\rho = \frac{v_T}{\Omega_c}}$

$\rho_i \sim 3$ mm $\rho_e \sim 0.05$ mm	<<	1-2 meter cross section

$$\text{Confinement quality} \sim \left(\frac{R_{machine}}{\rho_i}\right)^2$$

$$\boldsymbol{\tau_E \sim H \cdot B^2 R^3}$$

Extra transport physics (turbulence, …)

Fusion gain determined by physics, technology, and size

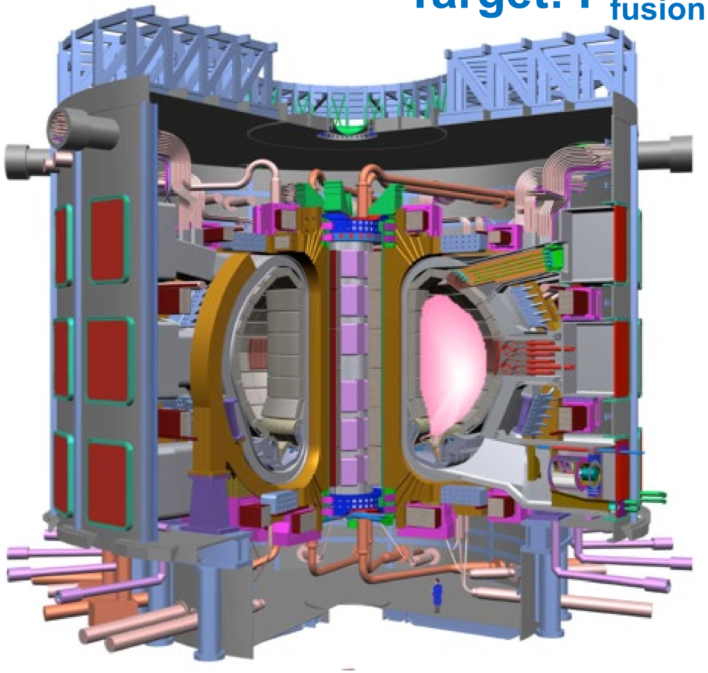
$$nT\tau_e \sim (\text{physics}) \cdot B^4 \cdot R^3$$

ITER being built to demonstrate large-scale fusion gain, technology integration, licensing and safety

$$nT\tau_e \sim (\text{physics}) \cdot B^4 \cdot R^3$$

ITER construction 78% complete (First plasma late 2020's)

Target: P_{fusion}=500 MW (Q_p=10) for minutes



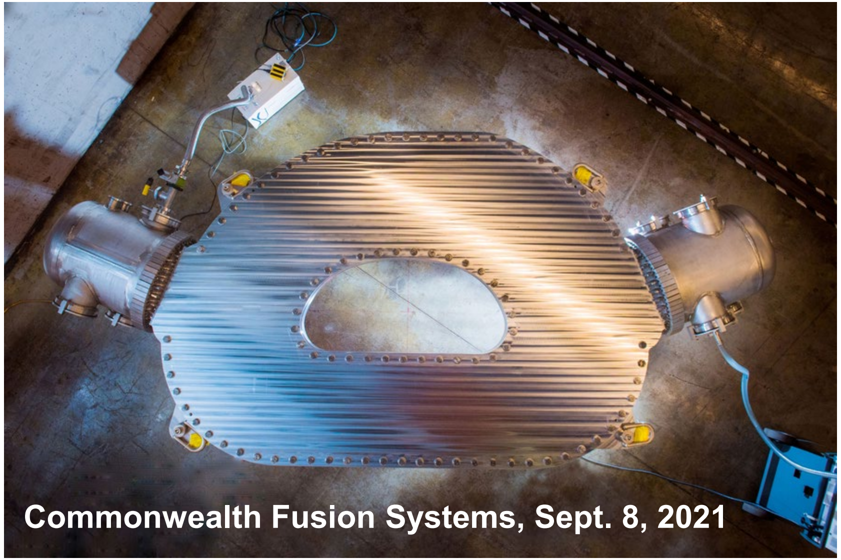
R~6 m, B_{coil}~12 T

(low-T_c Nb_3Sn superconductor)

Private companies are developing high-temperature superconductor fusion magnets to enable smaller scale

$$nT\tau_e \sim (\text{physics}) \cdot \mathbf{B}^4 \cdot R^3$$

20T large-bore high-T_c (REBCO) magnet demonstration



Commonwealth Fusion Systems, Sept. 8, 2021

CFS is targeting P_{fusion}=150 MW, Q_p=11 demonstration at R<2 m (SPARC)

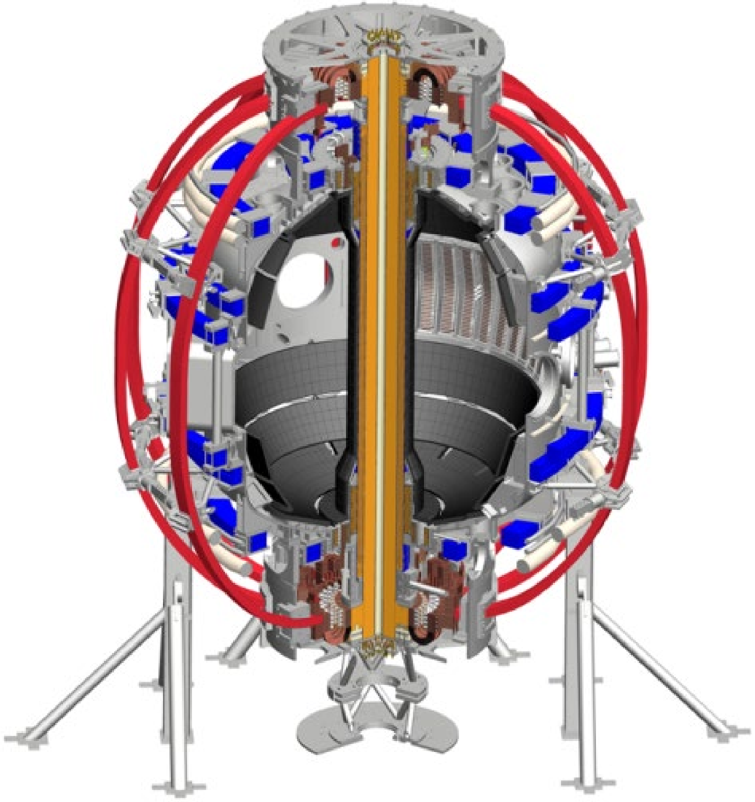
The US program (DOE-Fusion Energy Sciences) has focused a lot on advancing the physics basis of magnetic confinement

$$nT\tau_e \sim (\beta \cdot H) \cdot B^4 \cdot R^3$$

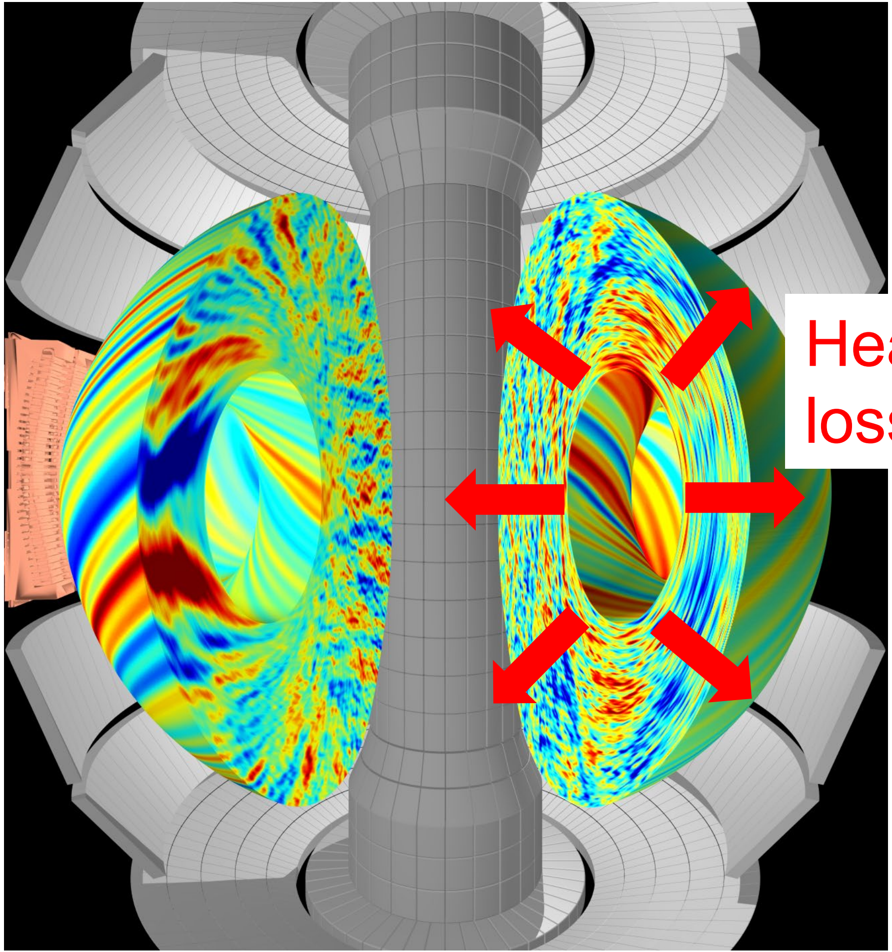
NSTX-U Research focuses on optimizing plasma performance including:

- **Confinement physics, H**
- **Macroscopic stability at high normalized pressure:**

$$\beta = \frac{nT}{B^2/2\mu_0} = \frac{\text{thermal pressure}}{\text{magnetic pressure}}$$



My recent research career has focused on studying and predicting turbulent energy loss in magnetically confined fusion plasmas



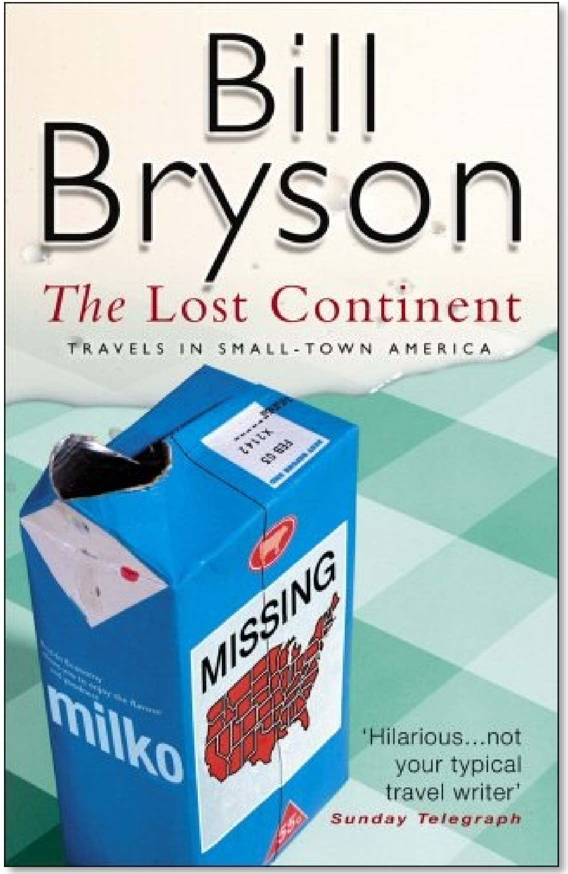
$$\tau_E \sim \frac{nT \cdot V}{P_{loss}} \sim H \cdot B^2 R^3$$

How did I get here?

I had no idea I would end up doing this and loving it … until I was doing it

"I come from Des Moines. Somebody had to." (The Lost Continent, B. Bryson)

https://www.traveliowa.com/cities/des-moines-iowa/721/

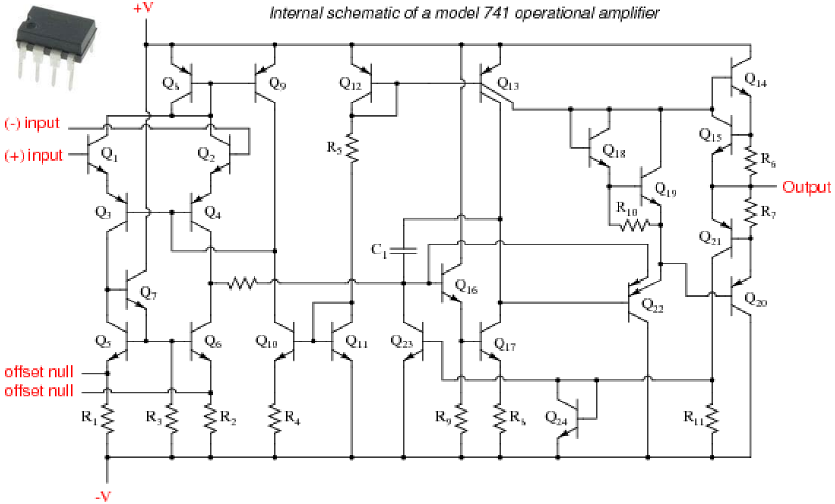


Studied electrical engineering at Milwaukee School of Engineering
Was just "going to get a job", but fascinated by too much

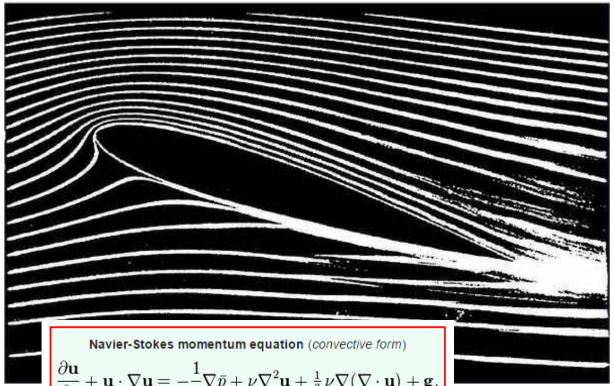
Discovered the broader beauty & magic of Maxwell's equations → knew I wanted to go on to graduate school

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$

I loved analog circuits (wannabe audiophile)



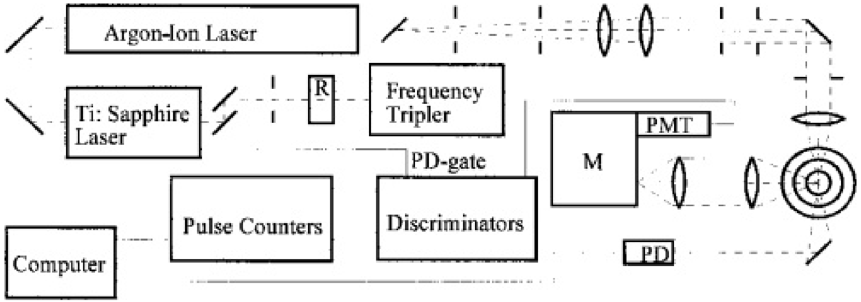
But I got distracted by fluid, thermo & aerodynamics

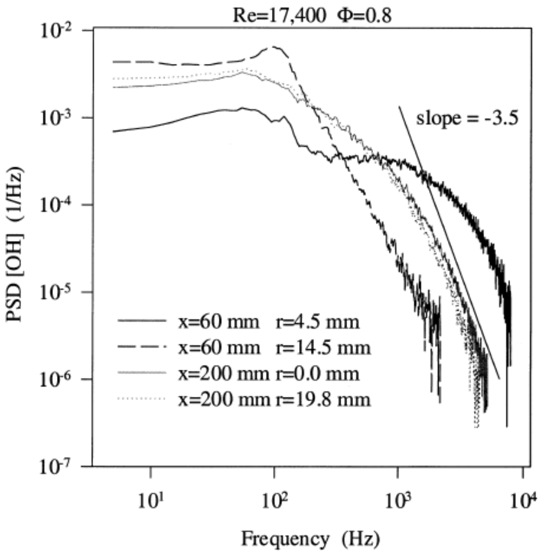


Navier-Stokes momentum equation *(convective form)*

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\frac{1}{\rho}\nabla\bar{p} + \nu\nabla^2\mathbf{u} + \tfrac{1}{3}\nu\nabla(\nabla\cdot\mathbf{u}) + \mathbf{g}.$$

Studied turbulent flames at Purdue University → my first intro to turbulence



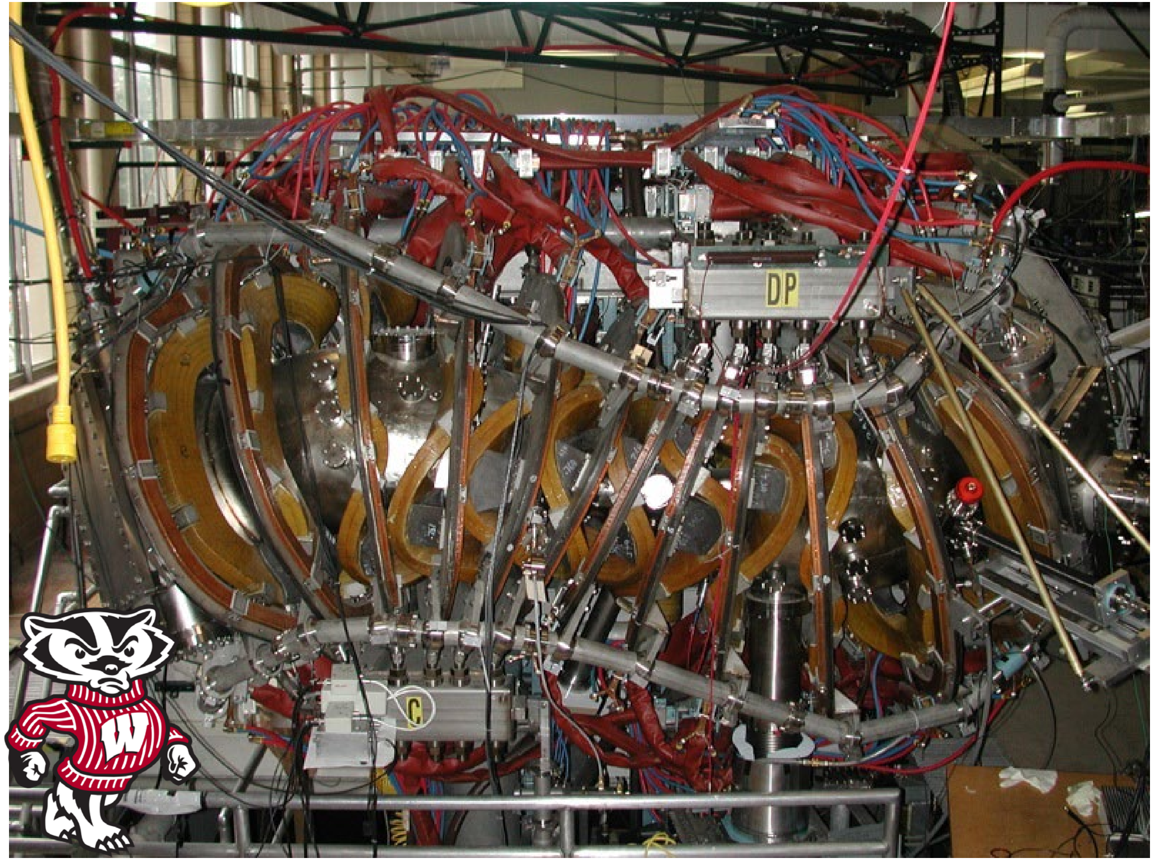


Used femtosecond lasers to measure hydroxl (OH) dynamics in turbulent flames

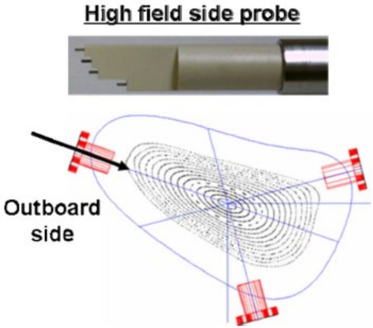
Was pretty fascinating, but I missed Maxwell's Eqs. → Plasmas!

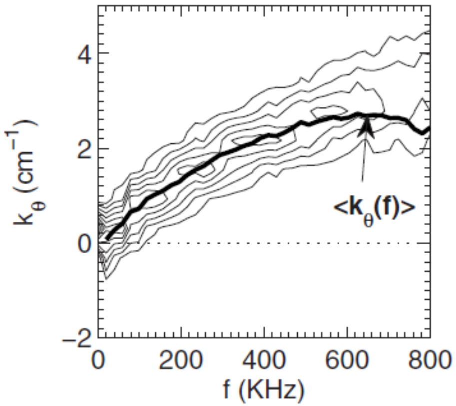
Did my Ph.D. at the University of Wisconsin – Madison studying magnetized fusion plasmas in the HSX stellarator

Helically Symmetric Experiment (HSX)



Used Langmuir probes to measure edge (cool) plasma turbulence





My current research expertise is running and validating direct numerical simulations of 5D kinetic plasma turbulence

$$\frac{\partial h_a}{\partial t} - i\left(\omega_\theta + \omega_\xi + \omega_{\mathrm{d}}\right) H_a + \frac{c}{\psi'}\left[f_{0a} + h_a, \Psi_a\right] = \sum_b C_{ab}^{\mathrm{GK}}$$

$$-\frac{1}{4\pi}\nabla_\perp^2 \delta\phi + \sum_a \frac{z_a^2 e^2}{T_a}\int d^3v\, f_{0a}\delta\phi = \sum_a z_a e \int d^3v\, \mathcal{G}_{0a} H_a\,,$$

$$-\frac{1}{4\pi}\nabla_\perp^2 \delta A_\parallel = \sum_a z_a e \int d^3v\, \frac{v_\parallel}{c}\mathcal{G}_{0a} H_a\,,$$

$$-\frac{1}{4\pi}\delta B_\parallel = \sum_a z_a e \int d^3v\, \frac{v_\perp^2}{\Omega_{ca} c}\mathcal{G}_{1a} H_a$$

5D gyrokinetic distribution

+

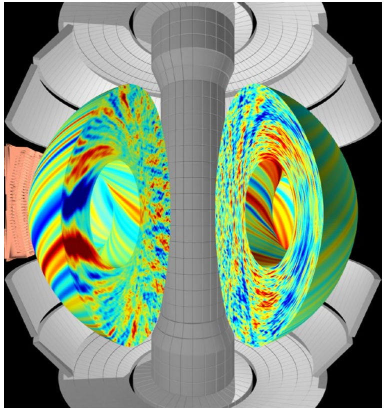
Maxwell's equations

+

Turbulence

= Finally, I've found my calling!

National Energy Research Scientific Computing Center (NERSC)



The fusion R&D landscape is evolving rapidly … and my career with it

Significant growth of investment-backed fusion companies, spending surpassing DOE Office of Fusion Energy Science

Private investors are serious about decarbonizing the climate by 2050

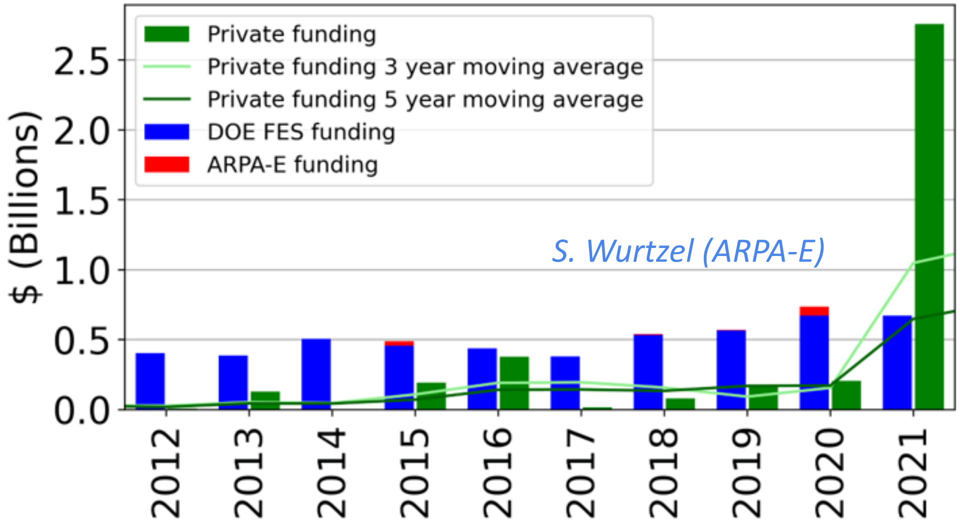
- Private companies can move fast, take bigger risks ("fail fast, fail cheap")
- Targeting first fusion pilot plants (FPP) in the 2030's

33 companies in Fusion Industry Association (FIA)

www.fusionindustryassociation.org

$5B+ total raised ($2.1B in 2021)

6 companies with $200M+



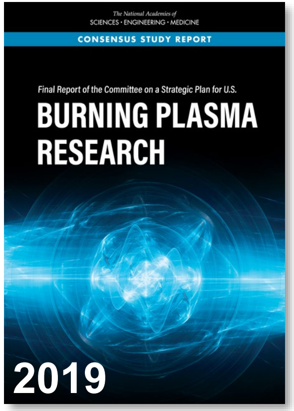
Growing industry has amplified the challenge of developing a diverse workforce

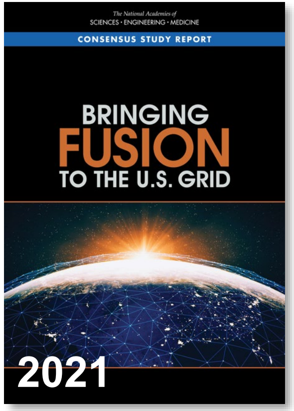
Recent White House Summit announced a "Bold Decadal Vision for Commercial Fusion Energy"

- **Fusion is 1 of 5 White House "net-zero game changers"**
- **Inclusive conversations at the Summit**
  - Net-zero, energy security/abundance, and U.S. technological leadership
  - Decades of progress enabled by sustained public support
  - Public engagement from the outset in support of energy justice
  - Private sector working to deliver carbon-free energy on timescale that matters
- **Currently enjoying bipartisan support**
  - House Fusion Energy Caucus
  - Senate Committee on Energy & Natural Resources

My perspective has been changed by these recent developments

National Academies reports outlining strategy for burning plasmas and fusion commercialization



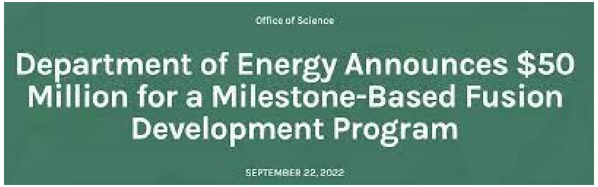


Fusion Energy Sciences Advisory Committee developed community-informed strategy

- **Growth of private companies & involvement in community planning workshops and activities has changed my perspective**
- **The prospect of commercial fusion energy (in my lifetime) has become real to me → I want to make a more direct, immediate impact**

New fusion public-private partnerships launched to accelerate R&D towards commercialization

Federal program encompasses decades of expertise → role to engage & support private industry to maximize success to commercialize fusion



2015-present
Modeled after DARPA
DOE funds teams (companies, universities, national labs) on potentially transformative applied R&D

2019-present
Modeled after NE GAIN
DOE directly funds national labs and universities to support specific industry needs (*company contributes 20% in cost-share*)

2022-present
Modeled after NASA COTS & NE ARDP
Companies deliver preliminary designs and R&D for fusion pilot plant, DOE reimburses companies (*up to 50% cost-share*) following successful completion of milestones

I took over as INFUSE Deputy Director in 2022

INFUSE cost-share program supports private industry via access to lab and university expertise & facilities

- **Open for companies to engage existing expertise and capabilities at all DOE labs & universities**
  - 1-2 year awards, meant to be quick (as quick as government contracts can move)
  - $250-$500k, company contributes at least 20%, DOE pays NL or university directly
  - 72 awards funded to date ($14.5M from DOE)
  - Awards to 21 U.S. companies partnering with 10 NLs and 8 universities

- **University researchers**: If you think you have an expertise or capability that would benefit a fusion company and would be interested in partnering, reach out to me and consider joining the University Fusion Association

Some recently awarded INFUSE projects (infuse.ornl.gov)

Project	Company	NL / University
High-temperature superconducting CORC® conductors for stellarator magnet applications	Type One Energy	LBNL
Performance-structure characterization to improve REBCO Fusion conductor production at SuperPower	SuperPower	Florida State U.
In-Field Performance Testing of a Novel HTS CICC for Practical and Cost-Effective Fusion Magnet Systems	General Atomics	BNL
Evaluation of the effect of coolant purity on the corrosion resistance of Castable Nanostructured Alloys for structural application in tokamak reactor blankets	Tokamak Energy	ORNL
Oxide Dispersion Strengthened Ferritic Steel Wire Feedstock Development for Large-Format Additive Manufacturing	CFS	PNNL
Retention of Fusion Plasma Species in PFC Candidate Fine-Grain Dispersion-Strengthened Tungsten Materials	Energy Driven Technologies	SNL
Machine learning assisted prediction of tungsten heavy alloy plasma facing component performance for fusion energy applications	CFS	MIT
FLARED -- Flowing Lithium's Adsorption and Release Experiment for Deuterium	Tokamak Energy	U. Illinois
Phase Diagram of Li-LiH,D,(T) Mixtures and Implications for Tritium Retention and Extraction	Renaissance Americas	SRNL
Model validation of low-density foams wetted with liquid deuterium and tritium for inertial fusion target optimization	Focused Energy	LLNL

What does the future hold, what are the challenges & opportunities?

Many materials and technical challenges need to be addressed through both public and private sectors

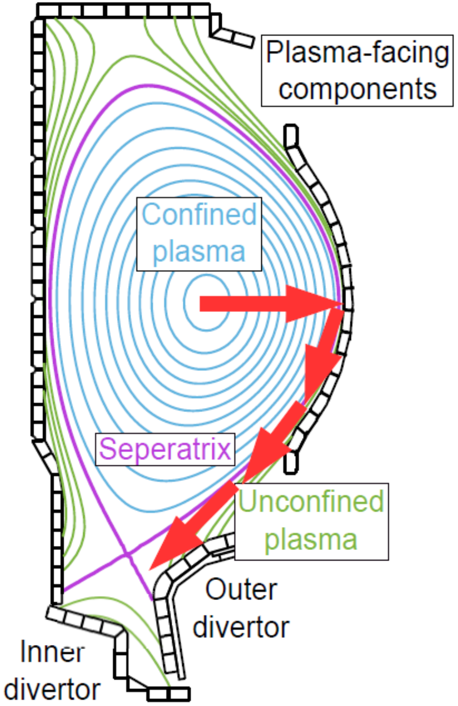
- **Need to harness plasma and neutron energy, breed tritium, and have structures with sufficient lifetimes**

- **Large energy and particle fluxes to plasma facing components (10+ MW/m^2)**
  - Chemical and physical sputtering, erosion and material migration, tritium retention …
- **14.1 MeV neutron irradiation**
  - Structural and functional material changes, transmutation, tritium migration & trapping …

- **Existing and growing university and lab programs in fusion nuclear science and plasma-materials areas, including new test facilities**
  - MPEX: Material Plasma Exposure Experiment (ORNL)
  - FPNS: Fusion Prototypic Neutron Source (concepts being evaluated)

Significant plasma and particle fluxes lead to a wide-variety of plasma-material interactions

- Chemical and physical sputtering, erosion and material migration, fuel retention



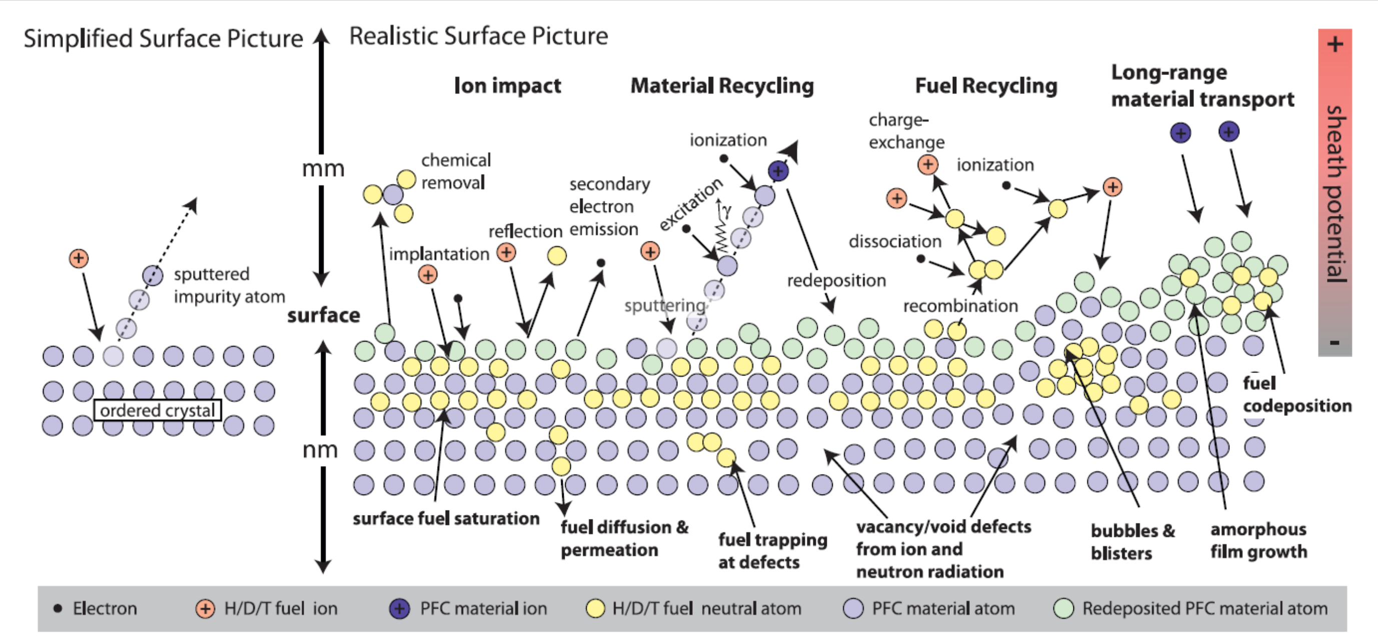
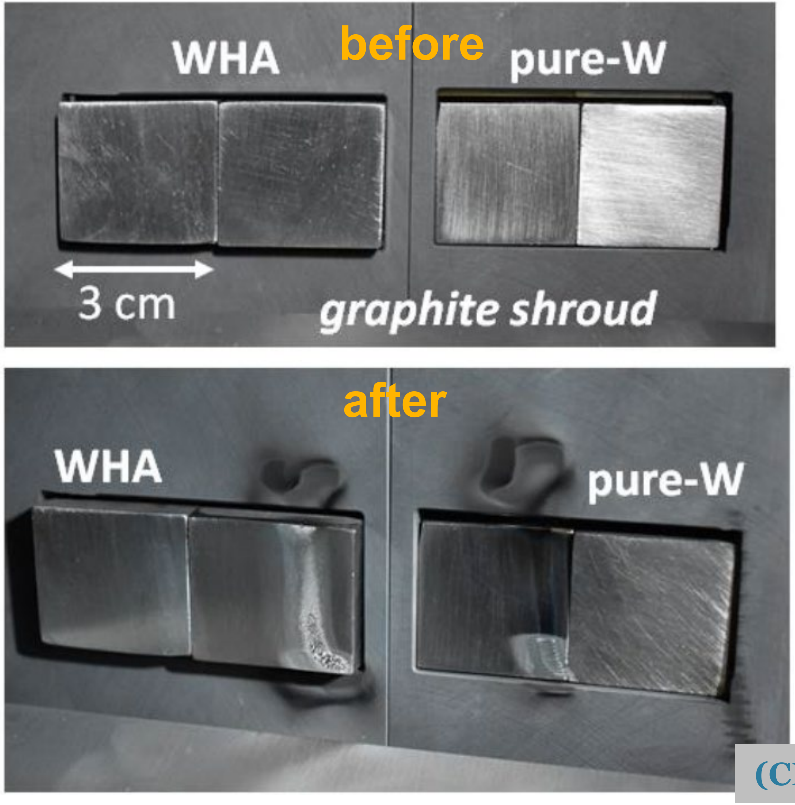


Figure 1. Schematic illustration of the complex, synergistic, and inherently multiscale surface interactions occurring at the material surface in a realistic magnetic fusion plasma environment. H, hydrogen; D, deuterium; T, tritium; PFC, plasma facing component; γ, gamma ray.

Wirth et al. (2011)

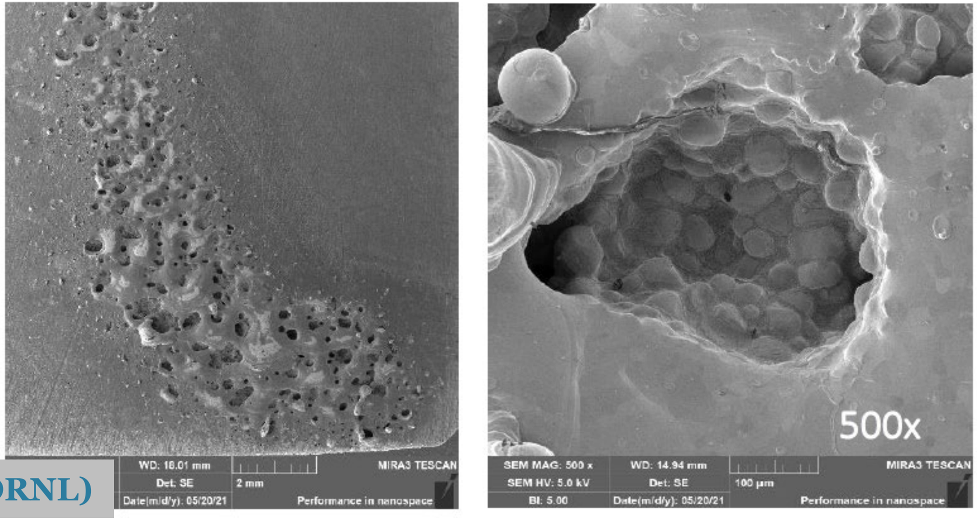
Example from INFUSE project: Testing W vs. W heavy alloy as a plasma facing component

~100 ms exposure of tungsten (W) and tungsten heavy allow (WHA) to 100 MW/m²



- Under intense transient exposure, WHA exhibited significant surface roughening and mass ejection
- Impacted decision of acceptable regions for using WHA in PFC design

WHA after exposure



(CFS + ORNL)

Material Plasma Exposure Experiment (MPEX) being constructed (ORNL) for material testing at reactor relevant fluxes and fluences

Table 1
MPEX ultimate performance parameters.

Parameter	MPEX Ultimate Performance Parameter
n_e target	up to $2 \times 10^{21}\,m^{-3}$
T_e target	up to 15 eV
T_i target	up to 20 eV
B target	1 T
Plasma diameter	3 to 10 cm
Γ_I target	$> 10^{24}\,m^{-2}s^{-1}$
Min angle of B to target	5°
q target, parallel	up to 40 MW/m^2
q target, perpendicular	10 MW/m^2
Total ion fluence	up to $10^{31}\,m^{-2}$

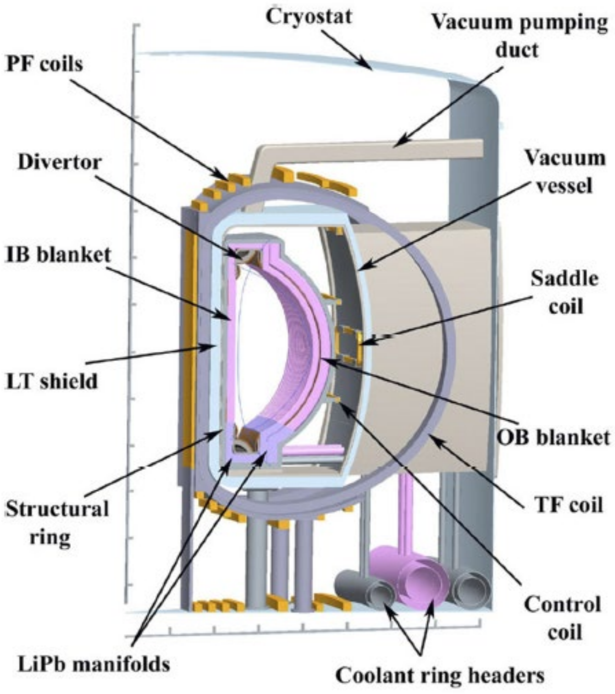
J. Rapp (ORNL)

Need to transport heat, breed tritium, and have structures with sufficient lifetimes

A variety of material options to consider

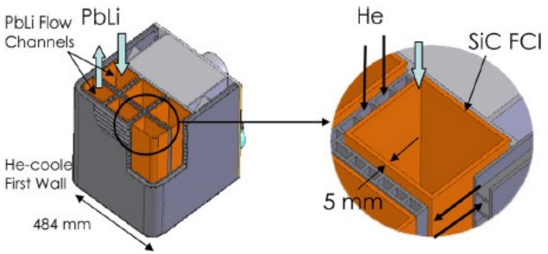
- Structure: reduced activation ferritic martensitic (RAFM) steel
- Tritium breeding material: ceramics - LiSO4 …, liquids – PbLi, FLiBe
- Coolant: He, PbLi, molten salt, water
- Neutron multipliers: Be, $Be_{17}Ti$, $Be_{17}V$, Pb
- Tritium permeation barriers: SiC, metal oxides, …
- Plasma facing components: W, …

One concept: Dual-cooled lead lithium (DCLL) breeder-blanket

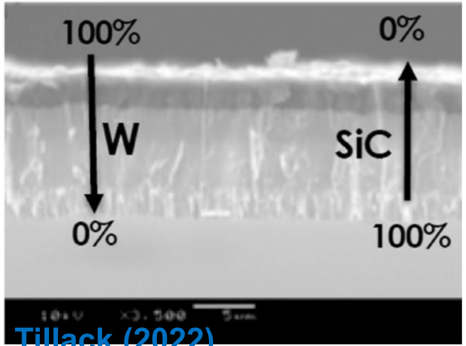


Tillack (2015)

Flowing lead-lithium (PbLi) with SiC inserts with He cooled "first wall"



Gradient-based materials composition (W-SiC) to optimize thermal conductivity vs. neutron resilience



Tillack (2022)

A number of structural and functional materials challenges associated with 14.1 MeV neutrons

- Structural damage (transmutation, swelling,)
- Material property changes (thermal conductivity, change in ductile-to-brittle transition)
- Considerable material experiments and model validation required for breeder-blanket & supporting structure
- Community is evaluating options for a Fusion Prototypic Neutron Source (FPNS)

Desired requirements for Fusion Prototypic Neutron Source (FPNS)

Parameter	Capability Requirement by 2028 or earlier	Capability Requirement by 2032 or earlier
Damage rate	5 to 11 dpa/calendar year (Fe equivalent)	15 dpa/calendar year (Fe equivalent)
Spectrum	Gaseous and solid transmutant generation rates consistent with 14 MeV fusion neutron	Gaseous and solid transmutant generation rates consistent with 14 MeV fusion neutron
Sample volume in high flux zone	$\geq 50\ cm^3$	$\geq 300\ cm^3$
Temperature range	~300 to 1200°C	~300 to 1200°C
Temperature control	3 independently monitored and controlled regions	4 independently monitored and controlled regions
Flux gradient	$\leq$ 20%/cm in the plane of the sample	$\leq$ 20%/cm in the plane of the sample

https://www.epri.com/research/products/000000003002023917

Some of my personal realizations (some that I'm constantly relearning)

- **You can do anything, don't be afraid to grow into the next phase of your career (whether government, industry, or partnership)**

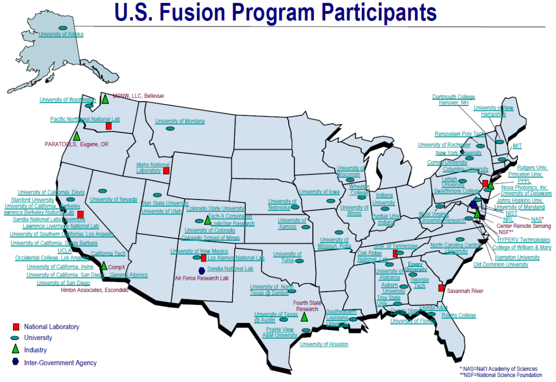
- **Prioritize what's important to you: you can't do everything *at one time*, setting boundaries is important (← I stink at this!)**

- **Look after your mental health!!! (see above bullet)**

- **Consider a career in fusion research, development & deployment! (see next slide)**

Many ways to get involved

- List of U.S. fusion institutions (funded by DOE/FES)
- University Fusion Association
- U.S. Fusion Outreach website ← see job postings (labs, uni's and private companies)

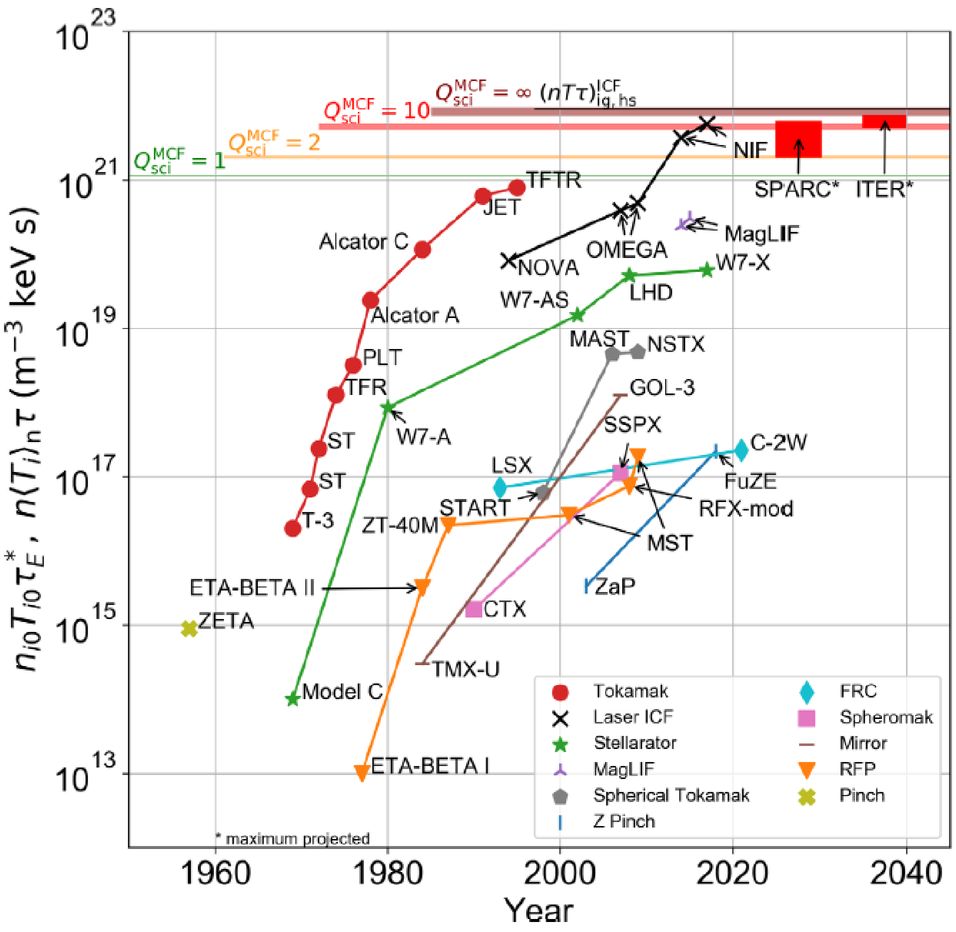


Fusion and plasma internships and summer schools

- Summer Undergraduate Laboratory Internship (SULI)
- Community College Internship (CCI)
- Plasma and Fusion Undergraduate Research Opportunities (PFURO)
- Graduate Summer School at PPPL

Link to these slides

Significant progress in fusion triple product



Wurzel, Hsu (2022)

Fusion community is embracing energy justice & social licensing now

- **Socio-technical challenge is as important as technical challenge**

- **Plant siting, fuel acquisition & waste disposal all have societal context**

- **Historically, energy deployment has greater burden on communities of color, with less share of benefits ← economic & energy justice**
  - Fusion energy community working towards bi-directional conversations with community groups to understand concerns, communicate benefits / burdens

- **Require community buy-in to avoid NIMBYism, i.e. “not in my backyard” ← social licensing**