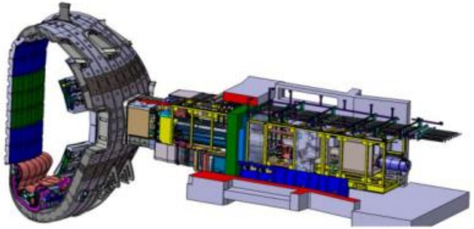
PRINCETON PLASMA PHYSICS LABORATORY

Overview of research highlights, growth, and diversification at PPPL

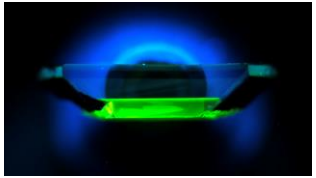
Fermilab Colloquium
June 21, 2023
Jonathan Menard – PPPL Deputy Director for Research

3 PPPL Missions

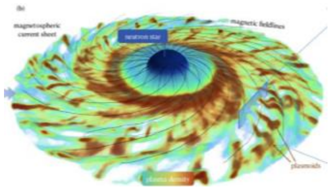
1. **Develop the scientific knowledge and advanced engineering to enable fusion to power the U.S. and the world**



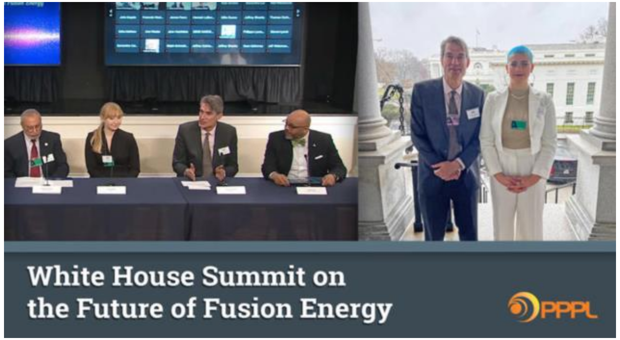
2. **Advance the science of nanoscale fabrication & sustainable manufacturing for technologies of tomorrow**

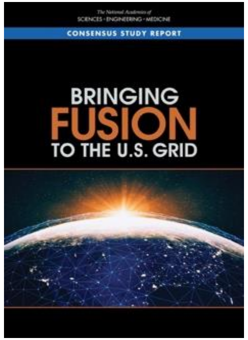


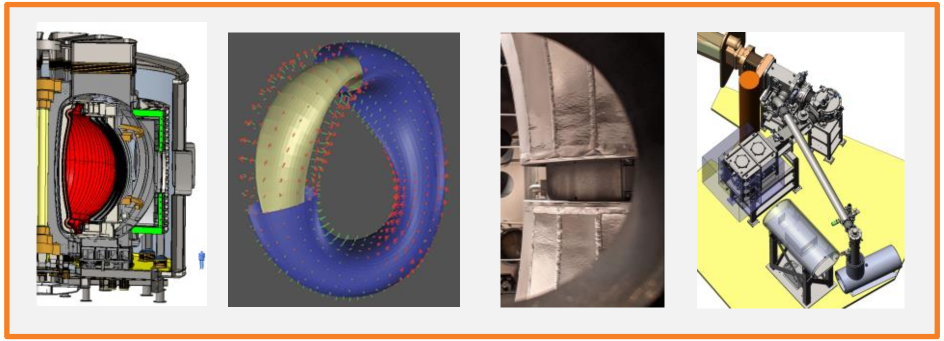
3. **Further the development of the scientific understanding of the plasma universe from laboratory to astrophysical scales**



Mission 1 - Supports Bold Decadal Vision for Fusion

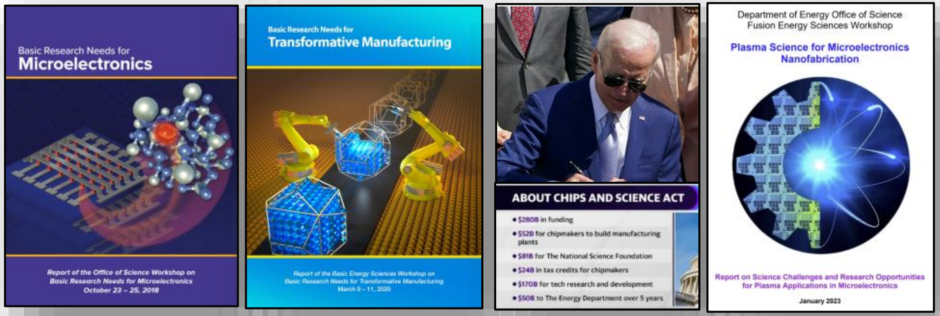




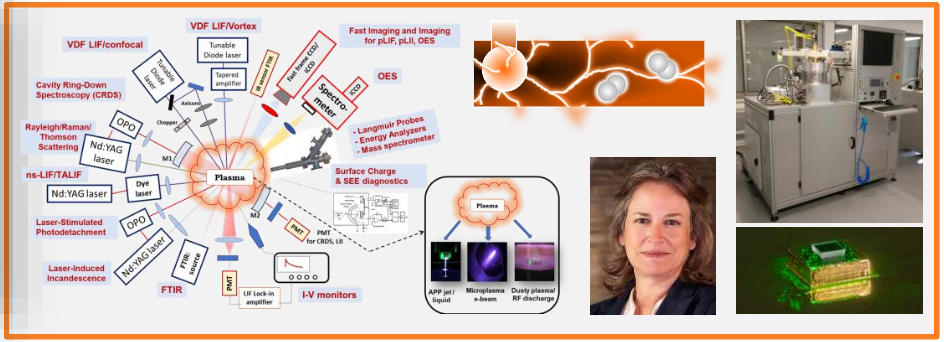


- Develop and understand innovations of interest to fusion industry
  - Spherical tokamaks, optimized stellarators, liquid metals, fusion diagnostics
- Predict performance with validated models (M3D-C1, XGC, TRANSP)
- Partnering with industry (e.g. recent Tokamak Energy T_i = 100M ºC)
  - Will partner with 5 companies in Milestone-Based Program (first Phase)
- Lead ITER diagnostics project, virtual engineering for fusion systems

Mission 2 - Supports US Microelectronics, QIS Vision



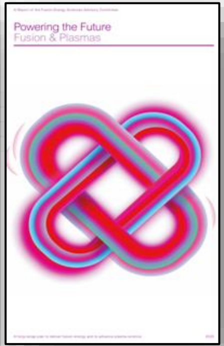
2018 DOE-SC Basic Research Needs for Microelectronics, 2020 Transformative Manufacturing, 2022 CHIPS and Science Act, 2023 FES Plasmas for Nanofabrication



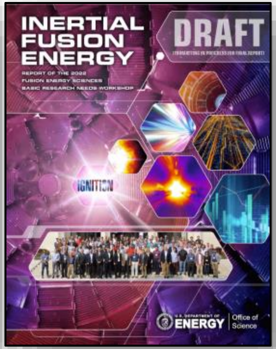
- Respond to growing demand for noninvasive optical diagnostics of processing plasmas in state-of-the art reactors working closely with industry
- Develop high-fidelity computational tools with fully kinetic treatment of plasma reactors, in 3D, with chemistry in plasma and at wafer surface
- Measure, understand, synthesize quantum-grade diamond for sensing, ultimately extend to wafer-scale for power electronics
- Launched new Applied Materials and Sustainability Sciences department with microelectronics, QIS, electro-manufacturing, and solar radiation management

Mission 3 - Supports FES Discovery Plasma Science Vision

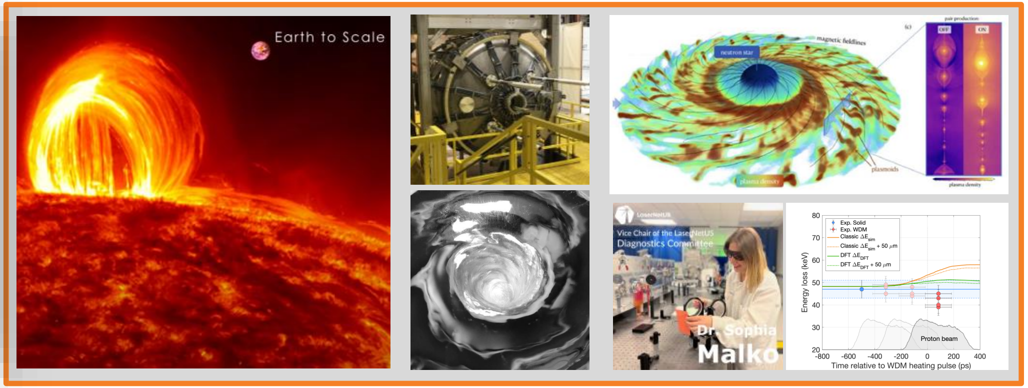
NASEM 2019-20



FESAC LRP 2020



IFE BRN 2022



- Provide world-leading collaborative research facility (FLARE) to measure fundamental magnetic reconnection processes (“plasmoid” instabilities)
- Understand turbulent momentum transport in accretion disks through laboratory measurement of the magneto-rotational instability (MRI)
- Contribute unique diagnostics and analysis to measure and understand warm dense matter states – with application to inertial fusion energy (IFE)
- Develop/use algorithms for exascale simulations of extreme astrophysical plasmas (e.g. black holes, n-star mergers), compare to multi-messenger data

A few strategic goals and perspectives for PPPL

- **Growth**
  - Why? PPPL is 2nd smallest DOE lab – important for long-term viability
  - How? Grow fusion and high-temp plasma physics AND diversify portfolio
  - What? Research spend has increased ~50% in past 4 years (~$100M → $150M / year) with a goal to increase to $200M+ in next several years

- **Diversification**
  - Leveraging and growing non-fusion low-temperature plasma capabilities
  - Nanofabrication, quantum materials / devices, electro-manufacturing
  - Areas vital for US economic security, support DOE sustainability vision

- **Fusion** and (hot) plasma physics are still by far the largest research activities at PPPL and will be for the foreseeable future

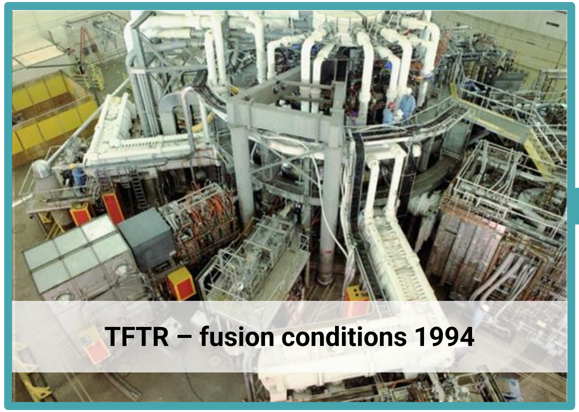
PRINCETON PLASMA PHYSICS LABORATORY

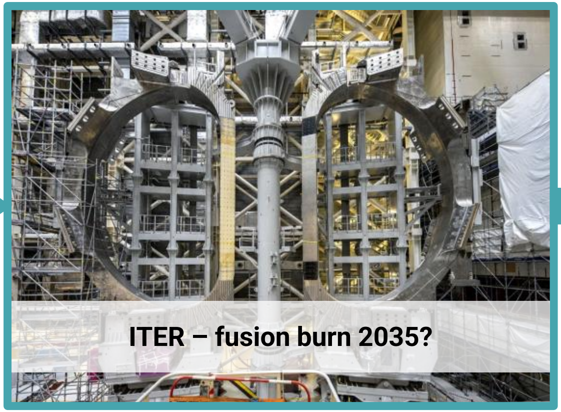
Mission 1: Fusion

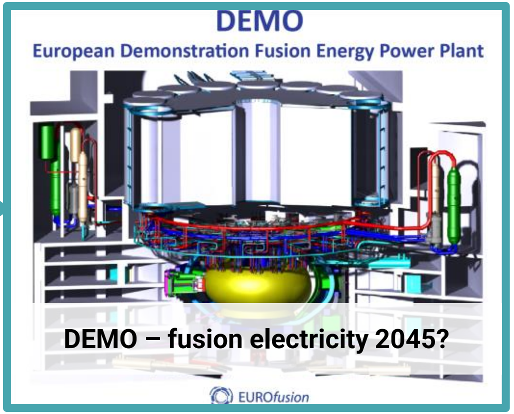
- Spherical Tokamak (ST) Motivation and Recent Research
- NSTX-U Recovery Project
- ITER diagnostics
- Domestic and international tokamak and stellarator research

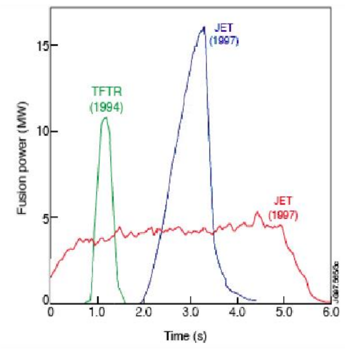
We need innovation if we want commercial fusion

| First the "main line" fusion is possible but ….







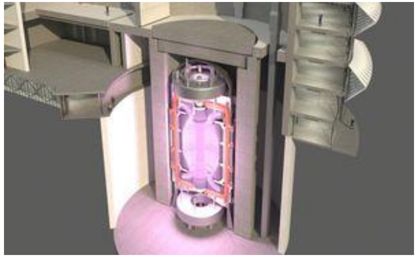


The EU DEMO is the logical conclusion of the conventional tokamak line. Unfortunately:

1. It is technically challenged – particularly power handling is not "solved."
2. It is very large and estimated to be very expensive.

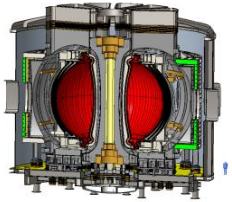
Substantial interest in low-A tokamak as Fusion Pilot Plant (FPP)

- UKAEA: Spherical Tokamak for Energy Production (STEP)



- Tokamak Energy: ST80-HTS, ST-E1

- PPPL: ST Advanced Reactor (STAR)
  - Understand reactor advantages and disadvantages for low-A / ST reactor
  - Prepare for milestone-based program

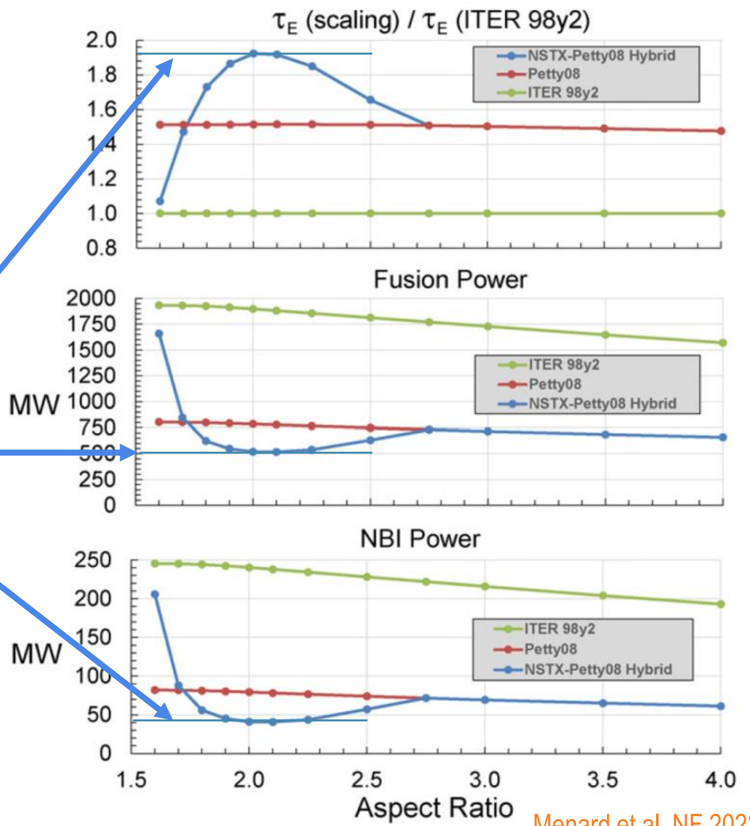


- Complements Advanced Tokamak FPP

ST confinement trends favorable for low-A FPP

- **Net electric power = 100MWe**
- 100% non-inductive current drive
- Tritium breeding ratio ≈ 1
- ReBCO TF lifetime = 10 FP-years
  - $B_{TF\text{-}max}$ = 18T, $J_{WP\text{-}TF}$ = 50 MA/m^2

- 2x higher confinement versus conventional-A
- 4x lower fusion power (same electric power)
- 5x lower heating power (same electric power)



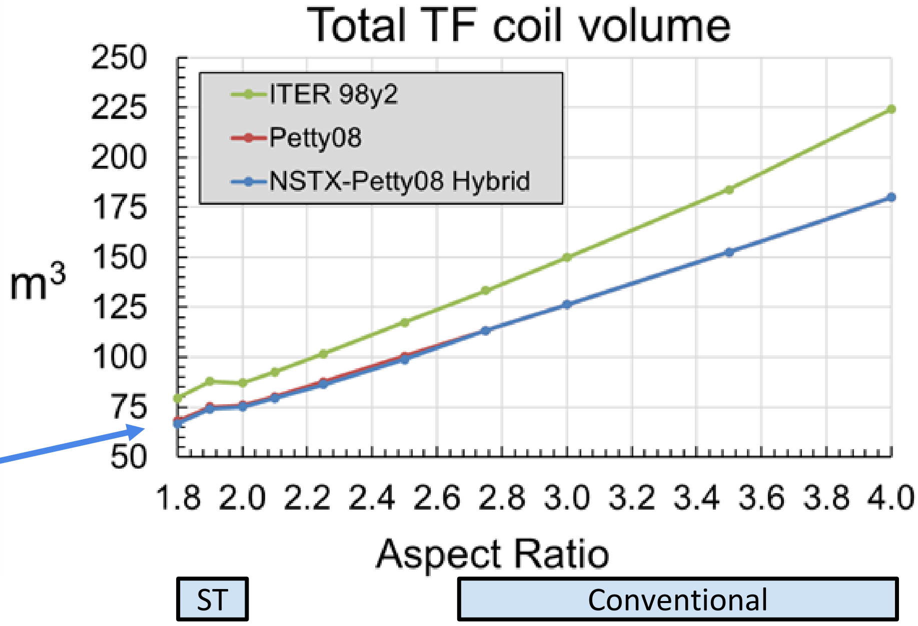
Menard et al, NF 2022

ST may be lower cost path to FPP

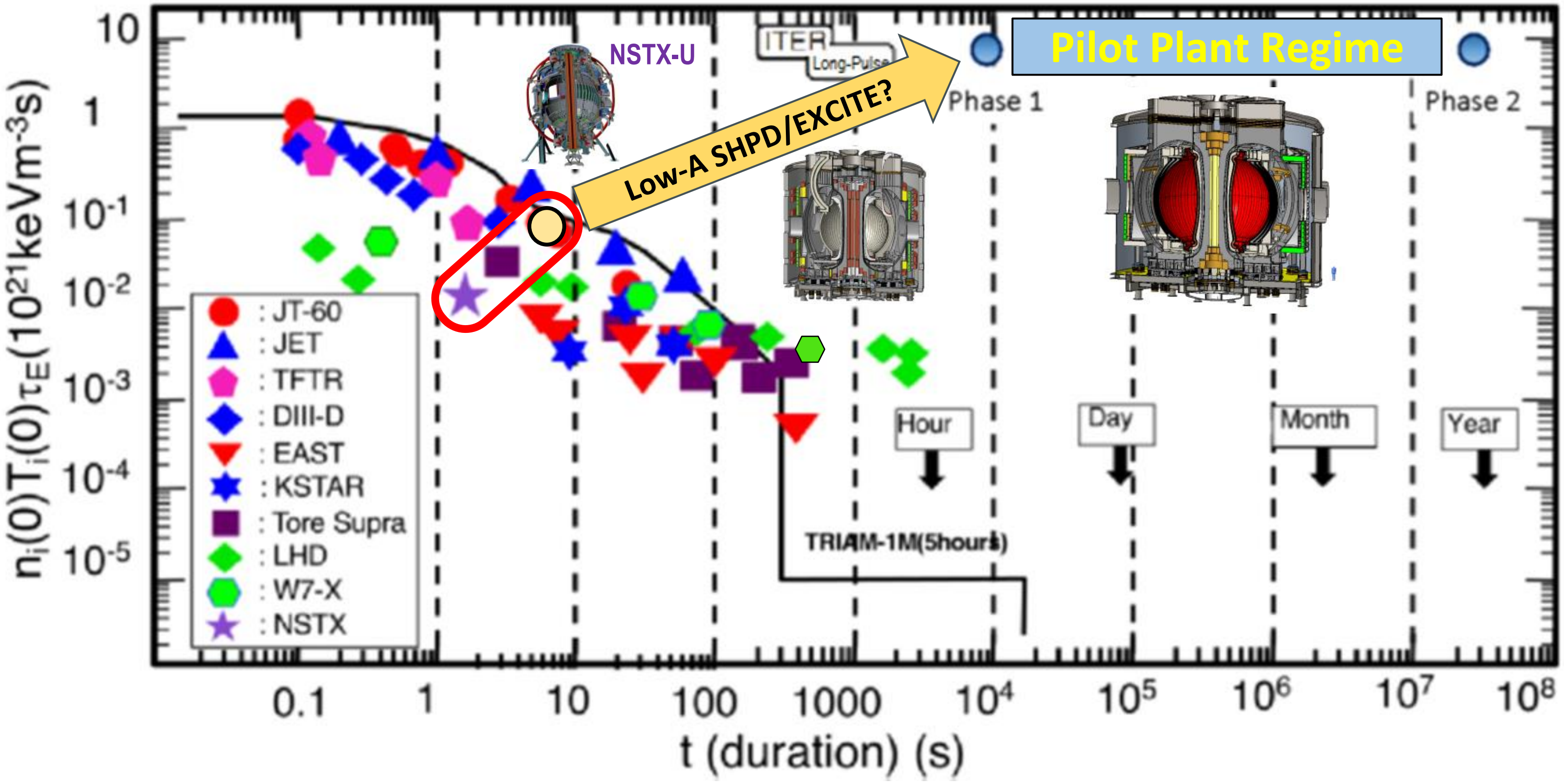
- Spherical Tokamaks (STs) have potential to reduce size and magnet mass and cost = major device cost drivers
- Compact core = tight space for solenoid, inboard blankets, divertors

- **Net electric power = 100MWe**
- 100% non-inductive current drive
- Tritium breeding ratio ≈ 1
- ReBCO TF lifetime = 10 FP-years
  - $B_{TF\text{-}max}$ = 18T, $J_{WP\text{-}TF}$ = 50 MA/m^2

2-3x lower TF volume relative to conventional aspect ratio



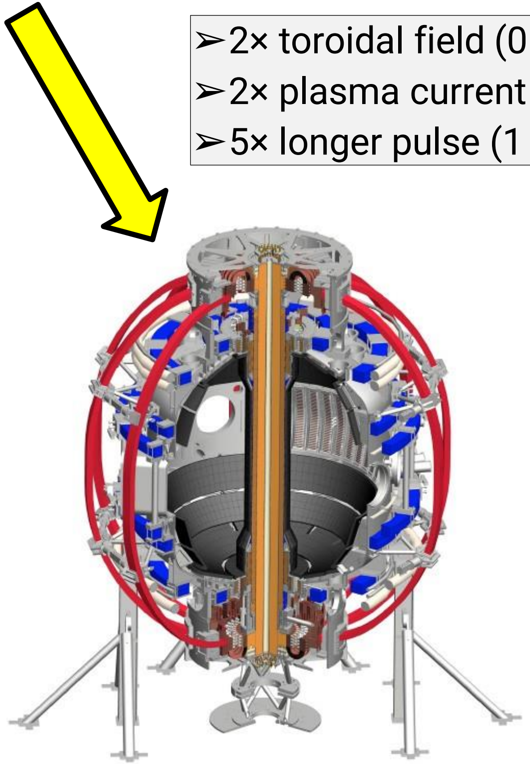
Magnetic fusion challenge: Sustaining high Q ($n_i T_i \tau_E$)



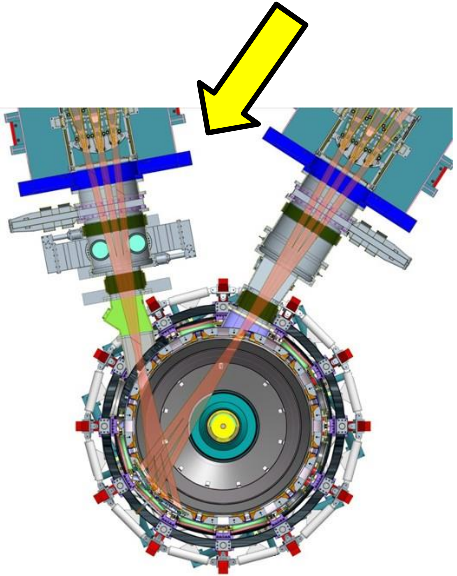
NSTX-U will (still) be most capable ST overall when completed

1. New Central Magnet

- ➢2× toroidal field (0.5 ➔ 1T)
- ➢2× plasma current (1 ➔ 2MA)
- ➢5× longer pulse (1 ➔ 5s)



2. Off-axis 2nd Neutral Beam

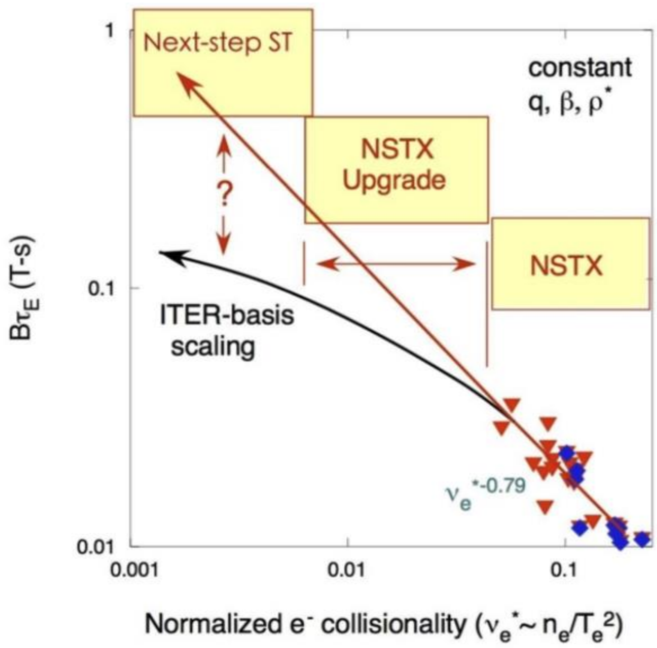


- ➢2× heating power (5 ➔ 10MW for 5s)
  - Tangential NBI ➔ 2× η_{cd}
  - Up to 15MW NBI + 4MW RF for 1-2s
- ➢Up to 10× higher $nT\tau_E$ (~MJ plasmas)
- ➢4× divertor heat flux (➔ ITER levels)

Enhanced capabilities to:

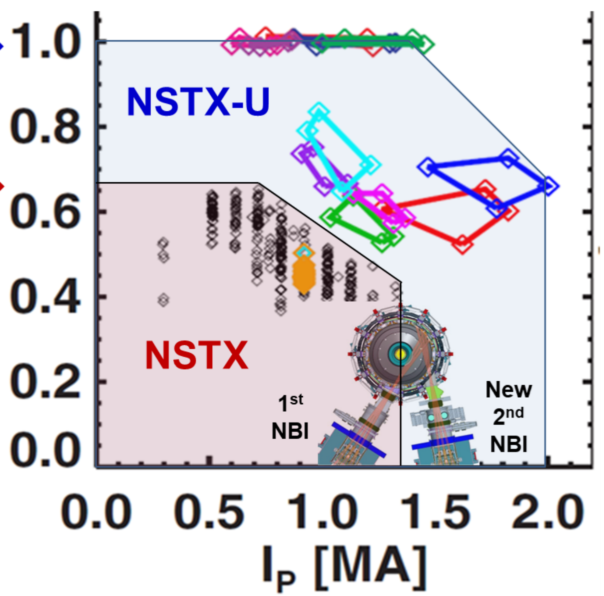
- *Study fundamental ST physics*
- *Provide low-A data for unifying tokamak physics across A*
- *Inform design of steady-state tokamak Fusion Pilot Plant*

NSTX-U foci: τ_E scaling vs ν_e*, 100% non-inductive current drive



NSTX-U greatly expands current operating space:
100% non-inductive at ~1MA, 5s
Plasma current up to 2MA for 5s

NSTX ≤ 65% non-inductive
I_P = 1MA for ~1s, 1.3MA for 0.2s



Gerhardt, NF (2012)

$B\tau \sim \nu_*^{-\alpha} \sim B_T^{4\alpha}$ (at constant q, $\rho*$, β_T)

α = 0.2 (~ITER98y,2)
α = 0.8 (ST scaling)

Advancing ST temperature profile predictive capability: TGLF predictions can reproduce NSTX profiles in some lower beta cases

- **At "low enough" beta, TGLF recovers T_e & T_i profiles, unifies physics basis over arbitrary R/a**

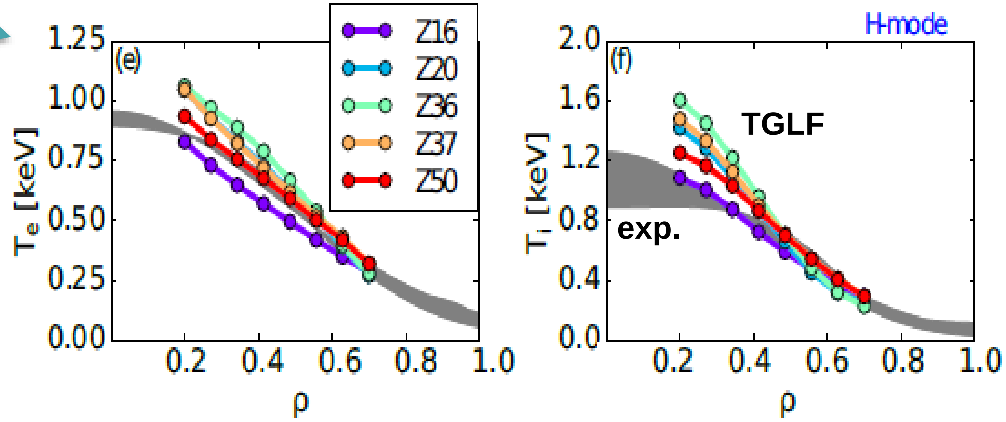
- L-mode: due to mix of ITG/TEM + ETG
  - Consistent with nonlinear gyrokinetics
- Modest-beta H-mode: due to ETG + neoclassical Q_i
  - ITG/TEM & MTM suppressed, consistent with gyrokinetics

- Sensitivity to uncertainties motivates future NSTX-U validation experiments

- Ongoing work to develop new gyrofluid closures more appropriate to high-β [Staebler]

T_e and T_i predictions using TGLF-TGYRO

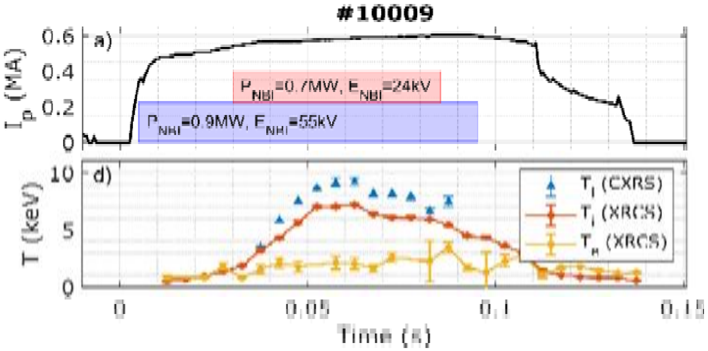
H-mode

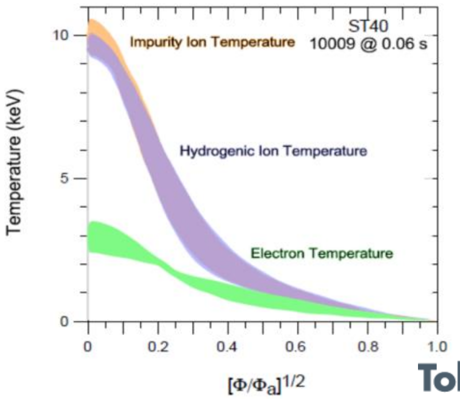


Avdeeva, APS (2022)

Diagnostic and transport analysis improve understanding of the achieved temperature in Tokamak Energy's ST40 (UK)

- ST40 has recently achieved their milestone of T_i > 100 M degrees K [1]
  - PPPL and ORNL researchers helped implement the charge exchange and x-ray crystal spectroscopy diagnostics that measure T_i
- Thomson scattering diagnostic now online to measure T_e and n_e
  - PPPL loaned data acquisition hardware to TE and consulted on real-time data acquisition
- TRANSP confirms high T_i in hot ion mode >> T_e, and close to measured impurity T [2]



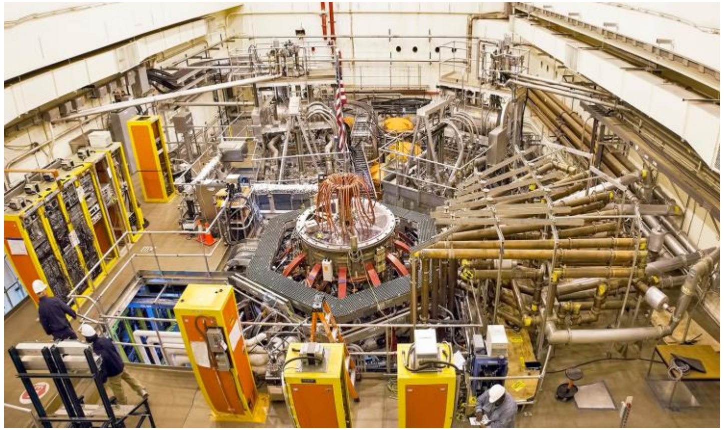


Helps NSTX-U/STs by exploiting our diagnostic and transport capabilities in new regimes and establishing conditions for enhanced confinement

Tokamak Energy

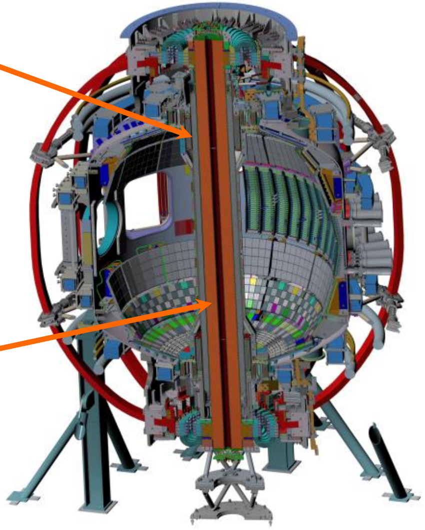
[1] S. McNamara et al., accepted by Nucl. Fusion (2023)
[2] S. Kaye et al., submitted to Nucl. Fusion (2023)

NSTX-U Recovery Project

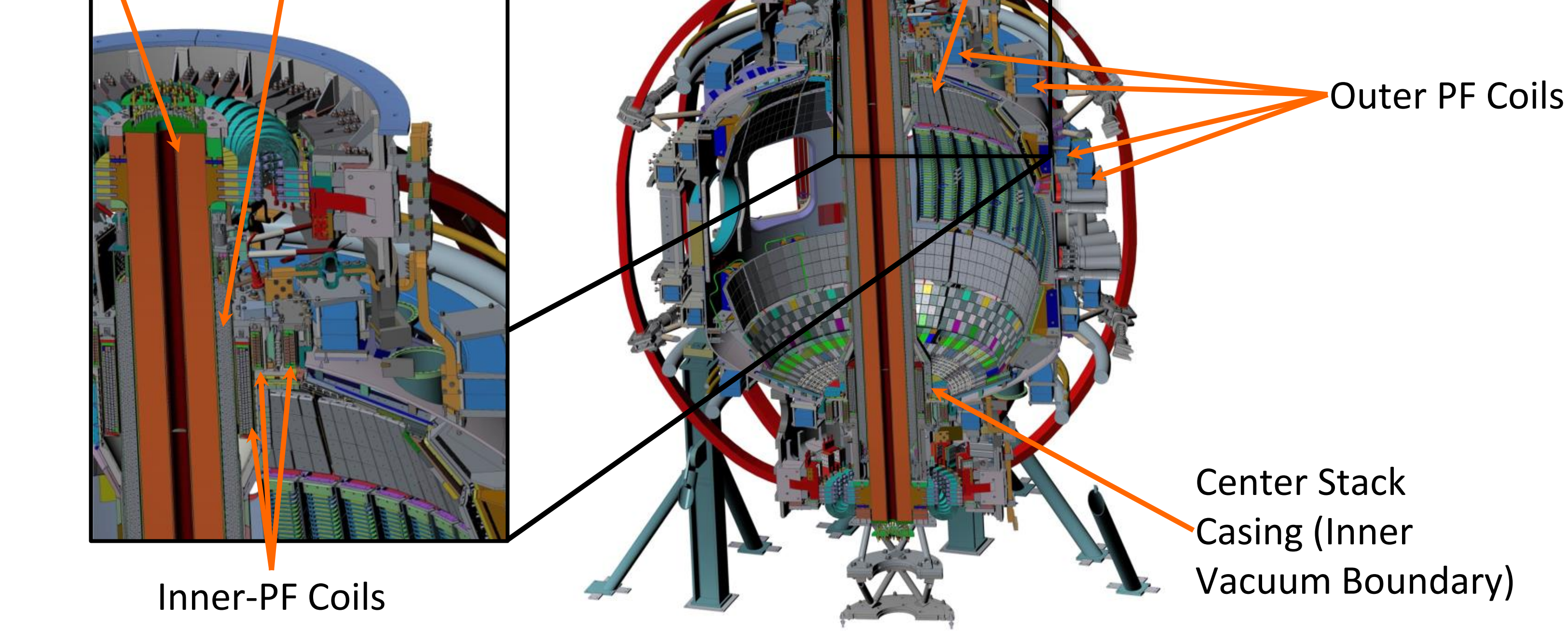


Some History:

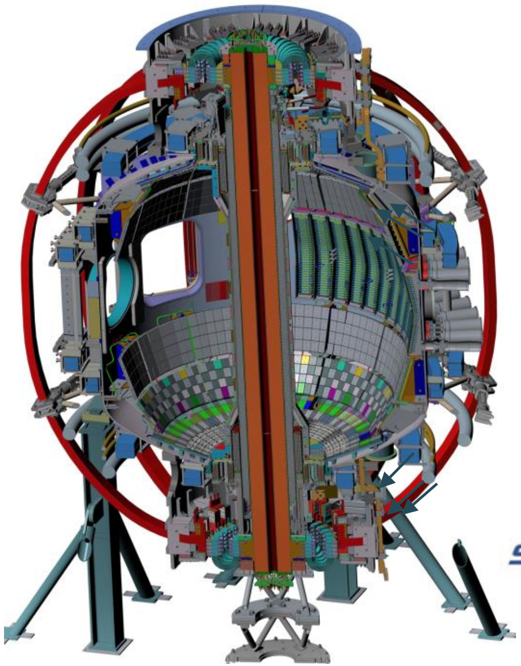
- Original NSTX Upgrade Project (2012-2015)
- NSTX-U commenced operation September 2015
- Operations ceased in 2016 after 10 weeks due to several technical issues (failed divertor PF coil…)
- 2017 Extent of Condition process defined initial scope of the NSTX-U Recovery Project
- Mission need affirmed 2018; project commenced
- Revised Project scope to include new Center Stack Casing (2019) and COVID cost & schedule impacts
- New TF/OH bundle (2021) added to project due to insulation degradation in Upgrade-era bundle
- Successfully rebaselined Project November 2022

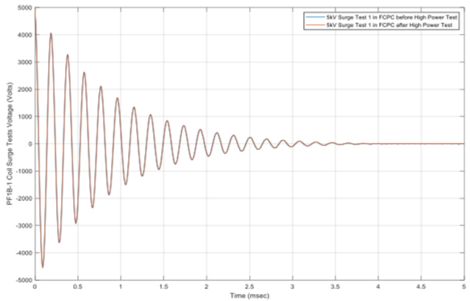


Recovery scope: New / modified components

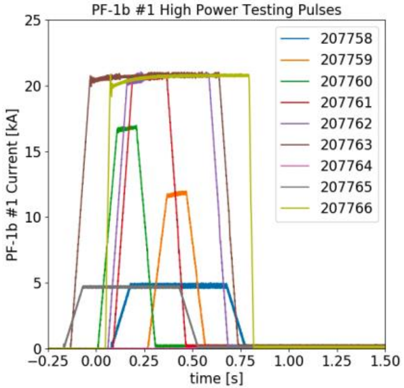


9 New Inner PF Coils COMPLETE (6 + 3 spare)

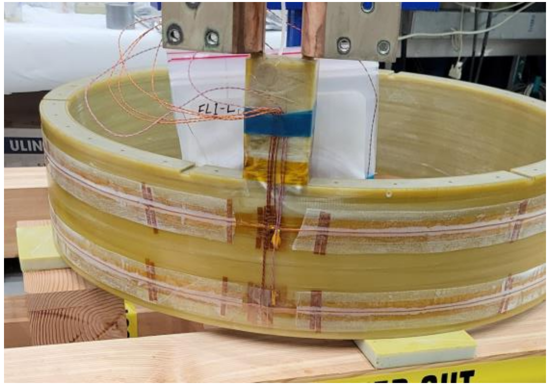


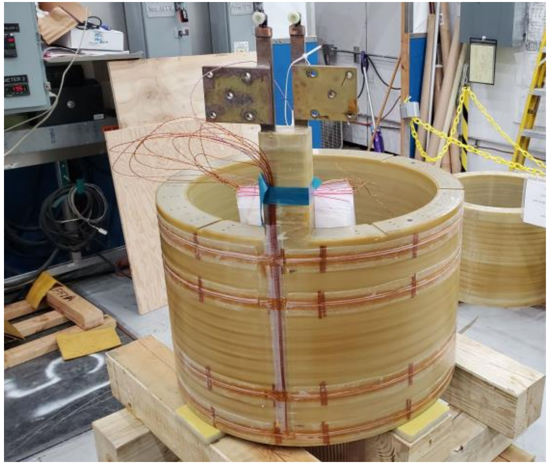


Before/After Surge Test



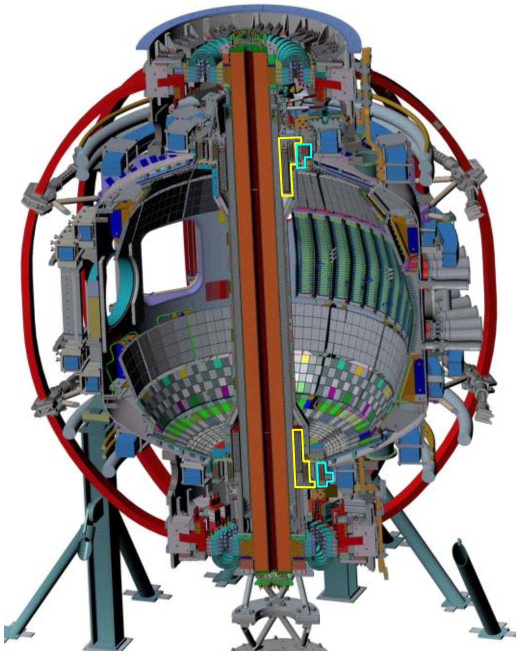
PF-1b #1 Waveforms





All inner-PF coils electrically surge tested, 6 primaries power tested

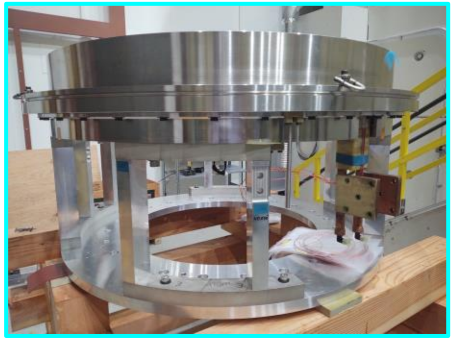
PF Coil Assemblies COMPLETE



Scope: Fabricate & install 4 inner-PF coil supports

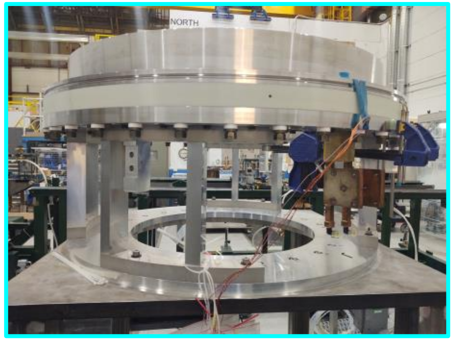
- ☑ Design
- ☑ Component fabrication
- ☑ Installations

PF-1a/-1b Assembly #1



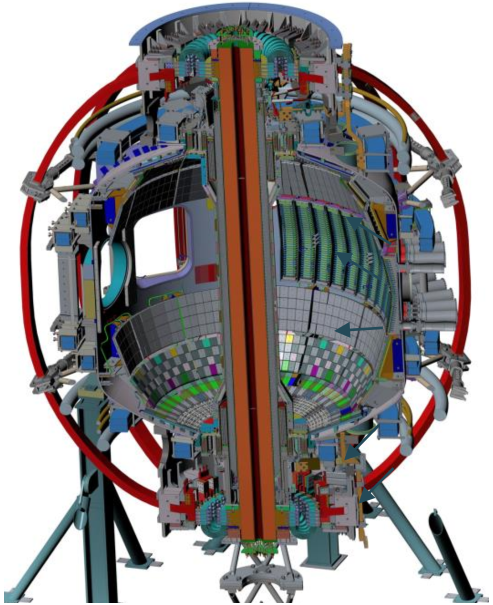
PF-1cL Assembly

PF-1a/-1b Assembly #2

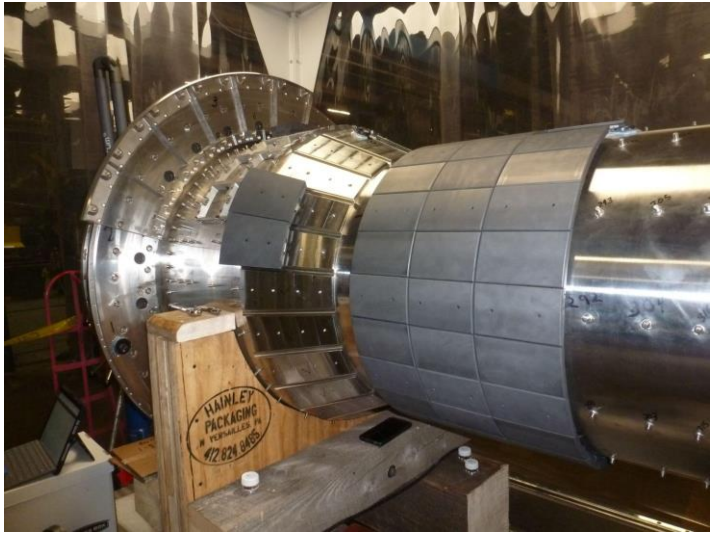


PF-1cU Assembly

CS Casing Fabrication COMPLETE



HOLTEC
INTERNATIONAL

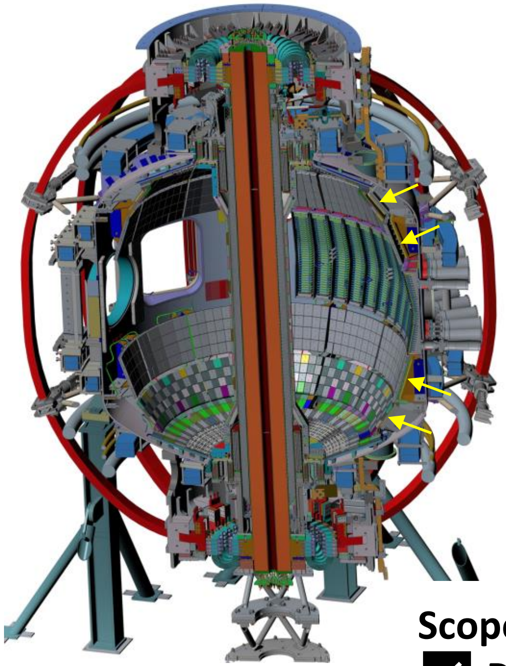


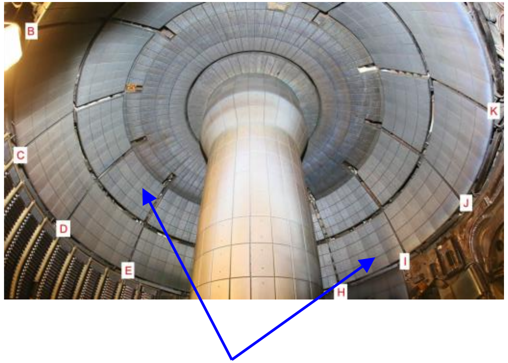
Scope: Fabricate In625 precision weldment = inner vacuum boundary

- ☑ Design
- ☑ Component fabrication (machining, welding, leak checking)
- ☑ Metrology and shipment

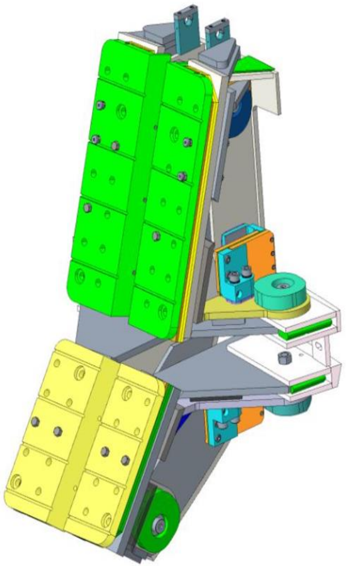
PFC trial fits ongoing

Passive Plate Reinforcements COMPLETE





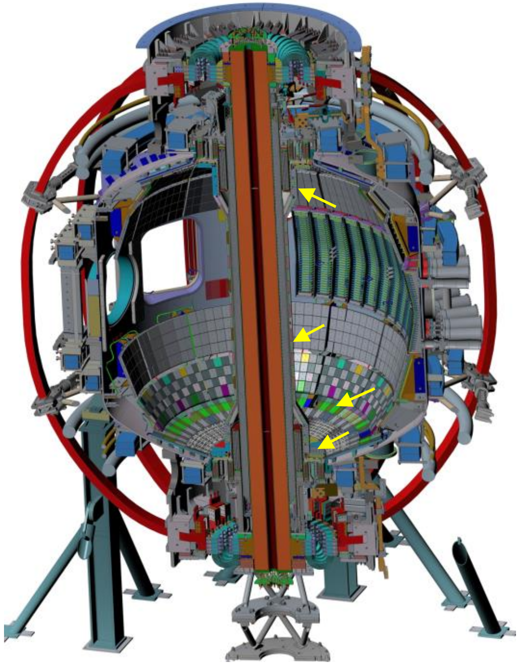
Discrete copper plates (Qty: 48), covered in tiles, mounted via in-vessel bracketry



Scope: Reinforce in-vessel bracketry, improve electrical continuity of joints

- ☑ Design
- ☑ Component fabrication
- ☑ Installations (weld reinforcements, brackets, shunts, all custom fit)

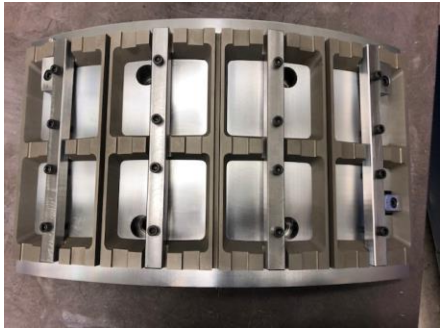
PFCs / Graphite Tiles COMPLETE

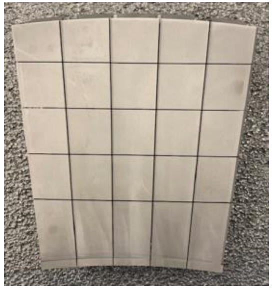


Scope: Fabricate ~1500 tiles and ~4600 metal components to install tiles

- [x] Design
- [x] Component fabrication
- [x] Create tile / metal part sub-assembly

Upcoming: In-Vessel tile trial fits ongoing





MWI

Stillwater TECHNOLOGIES LLC.

New Personnel Safety System (PSS) COMPLETE

NSTX-U is first fusion facility to be treated as a DOE Office of Science (SC) accelerator facility and subject to the Accelerator Safety Order (ASO)

Eliminates TFTR-era relay-logic and modernizes facility consistent with DOE standards and best practices

Trapped Key Exchange Blocks

Redundant Alarming ODH Monitors

PSS-SIS E-STOP and Search Station

PSS-SIS Position Sensing Switches on Neutral Beam Ground Switch

PSS-SIS Position Sensing Switches on Coil High Current Switch

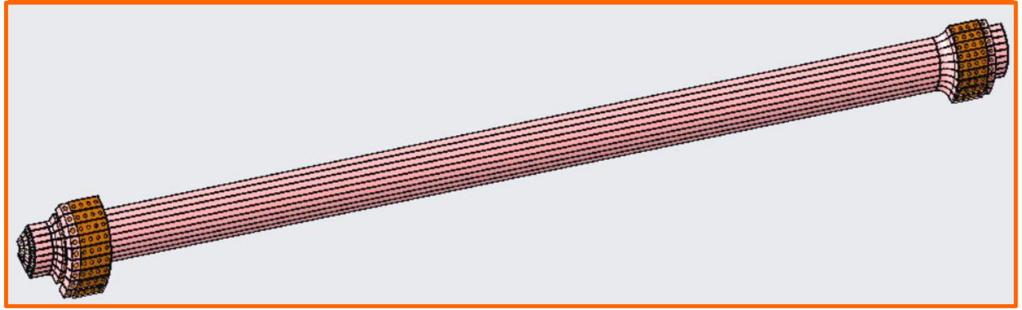
Steps to Fabricate NSTX-U TF Coil

Images from Legacy PPPL Fabrication

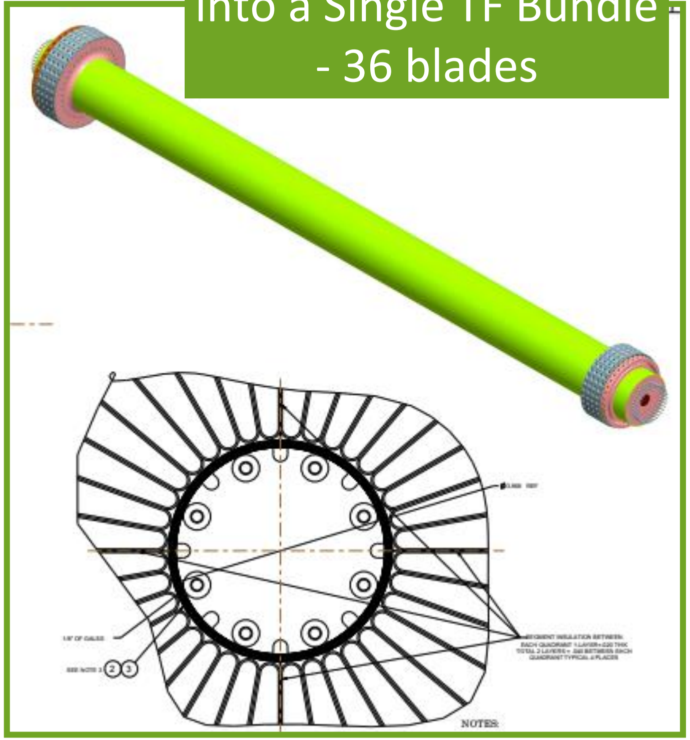
1: Fabricate TF Blades (Multiple Steps)

2: Insulate TF Blades

3: VPI Four Individual TF Quadrants - 9 Blades - do it four times



4: Combine Quadrants into a Single TF Bundle - 36 blades

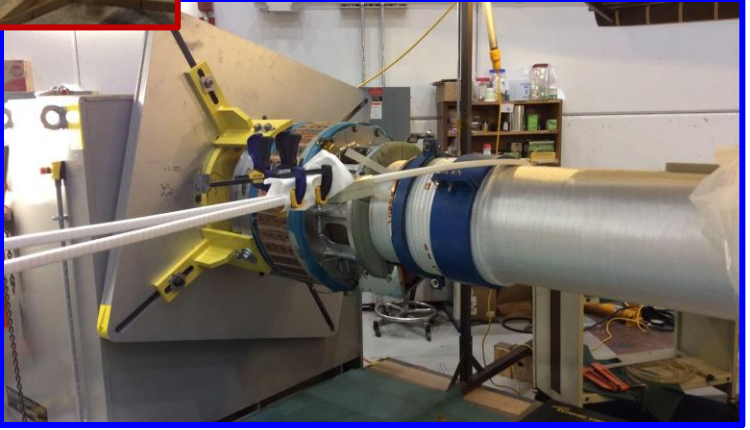


Steps to Fabricate NSTX-U OH Coil

Images from Legacy PPPL Fabrication

5: Fabricate and Prime OH Conductor

6: Wind an 888 turn solenoid on the TF



7: Vacuum Pressure Impregnation and Cure

PPPL managing production of conductor materials to be sent to magnet fabrication company ELYTT Energy (Spain)

TF Condutor Assemblies

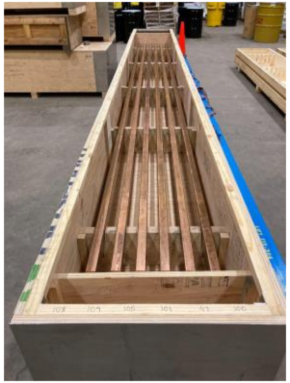
LUVATA Extrusions → DEARBORN BORTEC Gun Drilling → visioneering Pre-Machining → EWI Welding → visioneering Post-Machining → Ship to ELYTT

OH Conductors

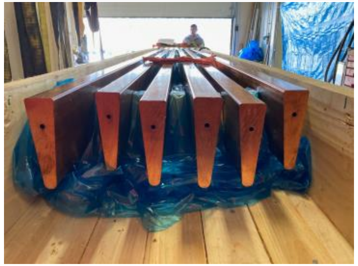
LUVATA Extrusions → Priming → Ship to ELYTT

OH Conductor Extrusions - DONE

TF Conductor Extrusions - DONE



Gun Drilled Conductors



Parts for Friction Stir Weld Trials

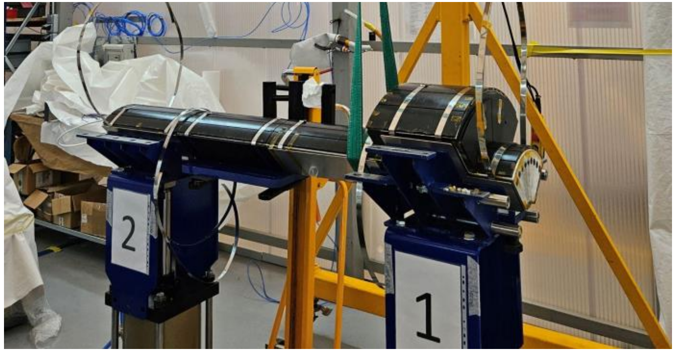
ELYTT progressing well on tooling, prototypes, production line

- Have established the facility, set up a clean room
- Focusing on prototypes and process development:
  - Insulation compaction testing
  - TF Quadrant Prototype
  - TF Bundle Assembly Prototype
  - OH Coil Prototype
- All activities to ensure that ELYTT is ready to build the bundle the right way, right away, when the first TF conductors are delivered

Completed mock-up VPI of TF Ground wrap

Clean Room with Quadrant VPI Prototype Tooling

Mock-up VPI of TF Quadrant assembly



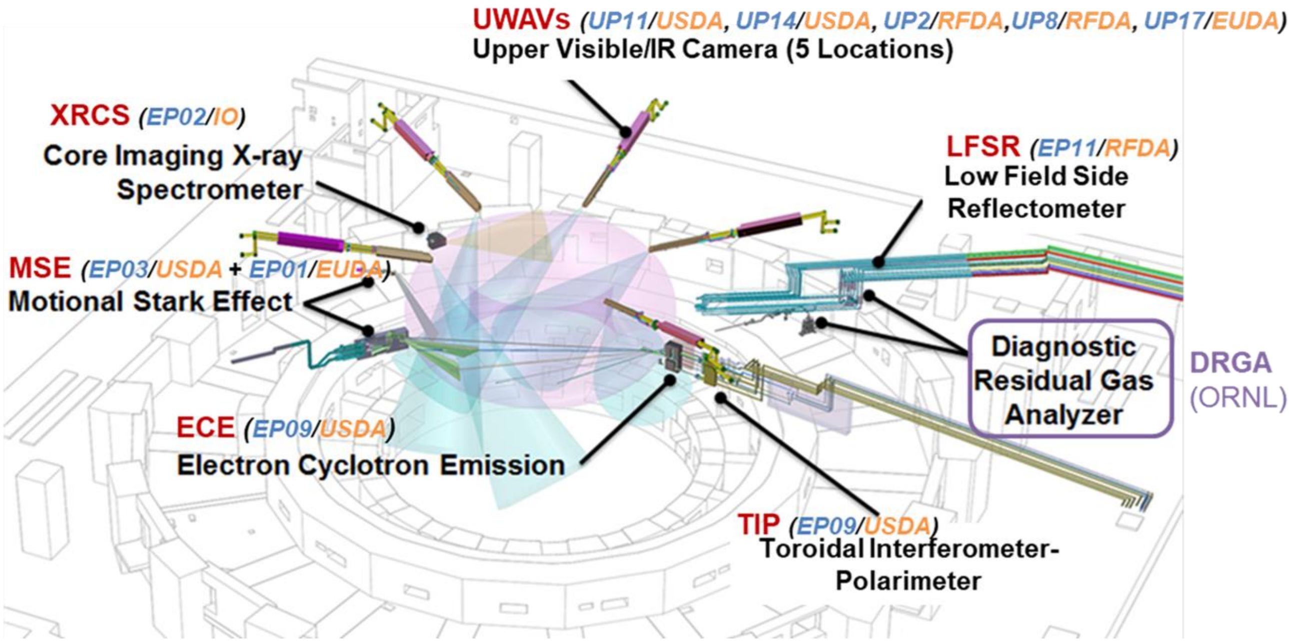
Recovery Project Baseline Schedule and TPC

- The critical path goes through TF/OH bundle fabrication, reassembly, and commissioning
- Early fit-up of key components off critical path reduces overall risk
- Schedule contingency derived from quantitative analysis of risk and uncertainty

Milestone	Date
TF/OH bundle delivery	May 2024
KPP 2 (PFC bakeout)	Jan 2025
KPP 3/4 (Coil energization / first plasmas)	Mar 2025
CDE4 - Early Finish	May 2025
CDE4 - Late Finish	Dec 2026

Total Project Cost (TPC) ~$360M (including ~$40M contingency)

PPPL-led US ITER diagnostics scope



DRGA (ORNL)

Key

UWAVs - Diagnostic

UP11 – Port No.

USDA – Port Integrator

- *USDA – U.S.A.*
- *RFDA – Russian Federation*
- *EUDA – European Union*
- *KODA – South Korea*
- *INDA – India*
- *JADA - Japan*
- *IO – ITER Organization*

The diagnostics systems measure profiles of:

- electron density
- electron temperature
- ion temperature
- impurity density
- plasma rotation
- fluctuations
- current density

Using:

- microwaves
- photons
- atoms

Tenants for US Ports

EP03 Tenants:

a. 18.GC Glow Discharge (IO)
b. 55.EB MSE (USDA)
c. 55.EC CXRS (RFDA)
d. 55.EF CXRS (RFDA)
e. 55.C5 TIP (USDA)
f. 55.G1 WAVS (EUDA)
g. 55.FA DIP (IO)

EP09 Tenants:

a. 55.G1 WAVS (EUDA)
b. 55.F1.0A ECE (USDA)
c. 55.F1.0C ECE (INDA)
d. 55.C5 TIP (USDA)

UP11 Tenants:

a. 55.B8 NAS (KODA)
b. 55.B3 MFC (JADA)
c. 55.GA UWAVS (USDA)

UP14 Tenants:

a. 18.GC GDC (IO)
b. 18.DM DMS (IO)
c. 55.GA UWAVS (USDA)
d. 55.GT PPMI (IO)

Notes:

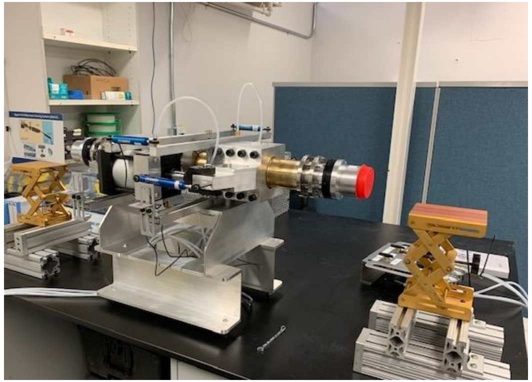
- DRGA is being progressed by ORNL
- Cost estimate:SP-1:$286M, Total funding SP-2: $354M, **TPC = $600-800M**

Technical Progress – Highlights

Low Field Side reflectometer (LFSR)

Measures edge electron density profile, fluctuations and plasma rotation using microwaves reflected off the plasma.

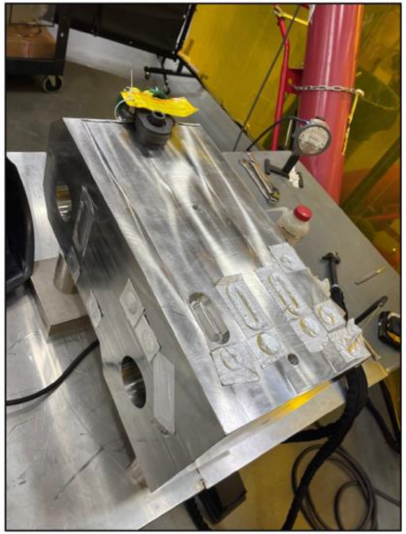
- Waveguide joint test moment loader prepared for Vector Network Analyzer installation at General Atomics



Test Antenna Block Assembly (TABA)

Antenna Block Assembly
Water Circuit Welding Trial

Antenna insertion trials



TABA Block Welding

Technical Progress – Highlights

Captive Components for TIP and LFSR

These are transmission line supports that had to be fabricated ahead of time to allow installation at the ITER site in France

First plasma diagnostics hardware delivery to the IO – arrived in Marseille July 2022

Motional Stark Effect (MSE)

Determines spectral properties of light emitted from H/D/T atoms injected by heating or neutral beams to determine magnitude of magnetic field as a function of position

Vacuum Chamber Installed – Mirror Cleaning Facility at PPPL
First plasma produced to prototype mirror cleaning methodology

Two DOE Early Career Award winners from PPPL in FY22 will lead major new research emphases on DIII-D and W7-X

- **Shaun Haskey: Main Ion Transport and Fueling in DIII-D Pedestal: From Formation to Sustainment**
  - Energy-resolved edge neutral density + AI/ML to accelerate analysis = new understanding of fueling relevant to burning plasmas

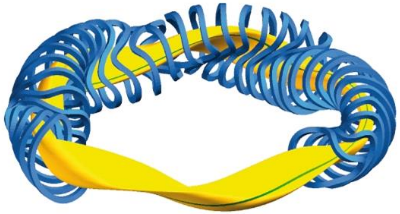
- **Ken Hammond: Pellet fueling and profile control in W7-X**
  - Real-time electron profile measurements + control Continuous Pellet Fueling System = profile control to reduce turbulence and transport
- Each award is $2.5M over 5 years

Many new opportunities with partnerships, alternative concepts

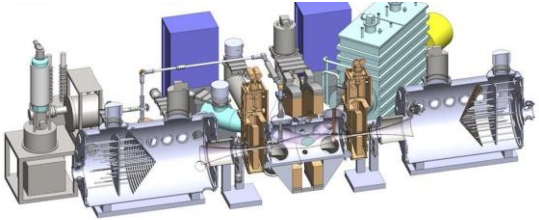
Stellarators (I_p~0)

LHD
@NIFS
Japan

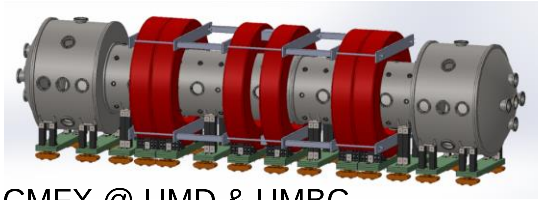
W7X
@MPIPP
Germany



New magnetic mirrors

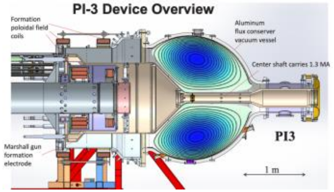


WHAM @ UW-Madison



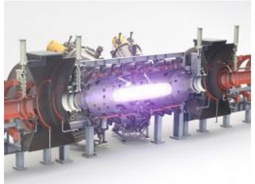
CMFX @ UMD & UMBC

GF



Zap

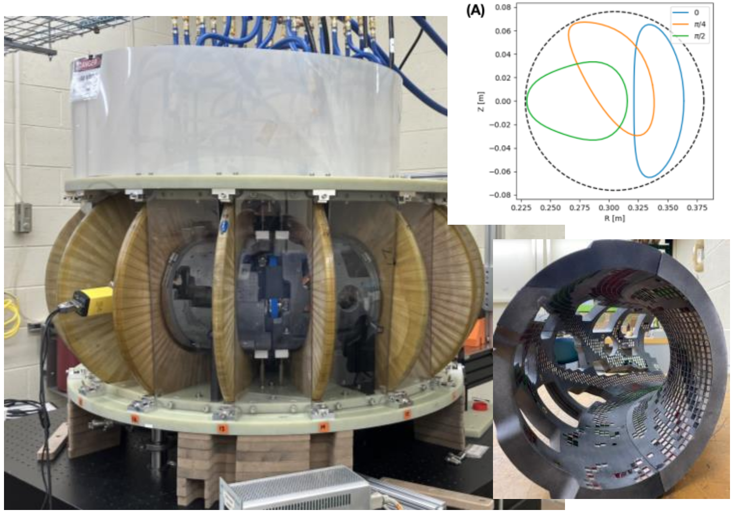
TAE

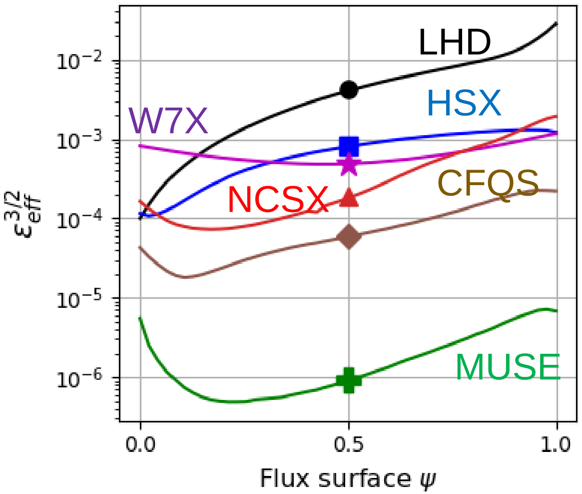


CFS

TE

PPPL's MUSE: World's first quasi-axisymmetric (QA) stellarator



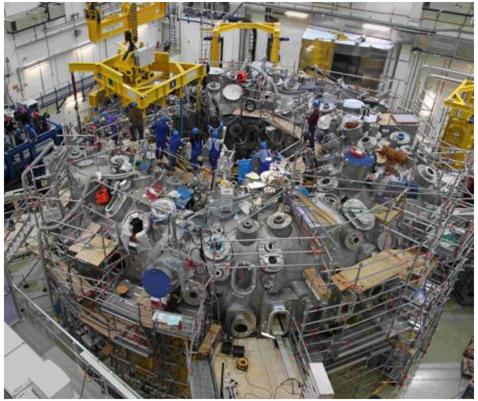


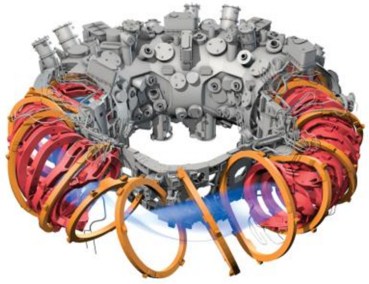
- Shaping field from **permanent magnets**
- Highly optimized configuration
- R = 0.30m, <a> = 4.4cm , B = 0.15T, 2 period
- Started e-beam mapping → tweak alignment
- Then flow-damping measurement (like HSX)

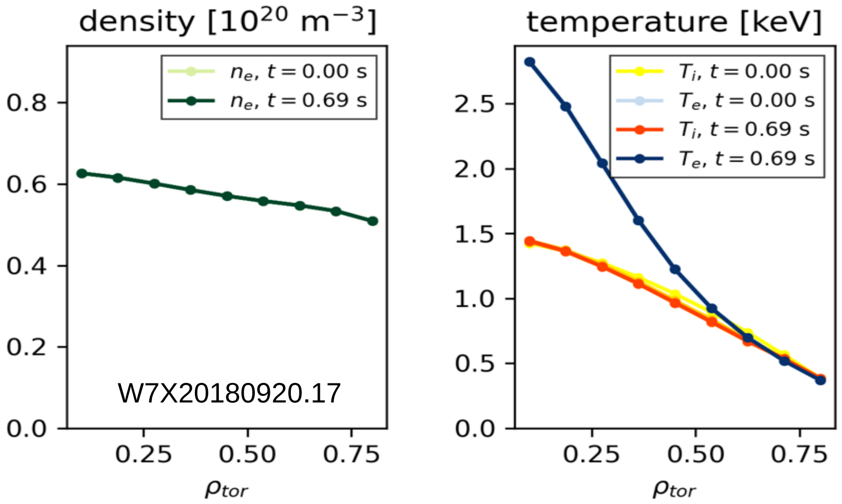
Physics Opportunities

- RF helicon heating (antennas in place, 2kW)
- Fundamental micro-stability measurements
- Stability studies, β ~ 5% accessible (ISS95)
- Test new optimized configurations
- **Great opportunity for students**

First transport modeling, successful profile prediction in W7-X







- Agreement between predicted (red) and measured experimental (yellow) T_i profile (right panel)
  - Predicting T_i profile only using GX, a new GPU-native gyrokinetic turbulence code for stellarators (and tokamaks)
- KNOSOS for neoclassical fluxes
- Trinity3D for macro-scale profile evolution

30 min on 16 GPUs

Mandell et al, arXiv:2209.06731 (2022)
Mandell et al, *J. Plasma Phys.* **84**, 905840108 (2018)
Barnes et al, *Phys. Plasmas* **17**, 056109 (2010)
Velasco et al, *J. Comput. Phys.* **418**, 109512 (2020)
https://gx.readthedocs.io
https://t3d.readthedocs.io

PRINCETON PLASMA PHYSICS LABORATORY

Mission 2: Nanofabrication, Sustainability

- Low-temperature plasma collaborative research facility
- Microelectronics
- Quantum diamond
- Electro-manufacturing

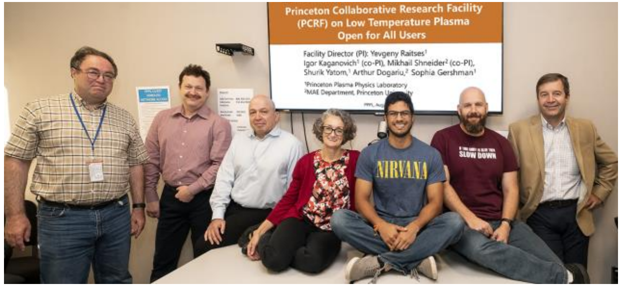
PPPL core LTP expertise and infrastructure

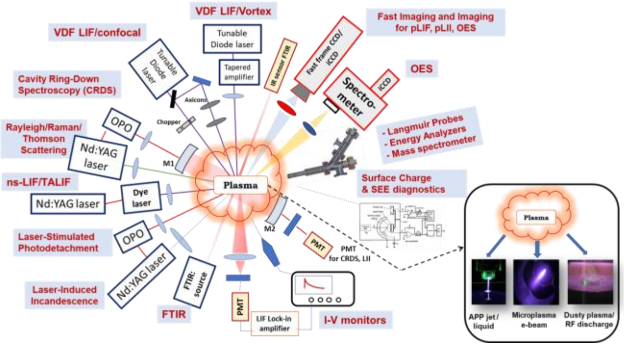
- Experiments: Nanosynthesis lab, plasma sources, propulsion lab
- Theory: Kinetic effects, instabilities, quantum chemistry
- Diagnostic measurements – Probes, lasers, spectroscopy

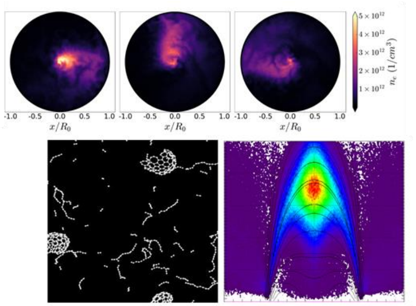
- Enhanced by:
  - **Collaboration with Princeton University experts** in materials science and chemistry, Princeton Institute for the Science and Technology of Materials and Andlinger Center For Energy And Environment
  - **High performance computing** experts involved in the DOE Exascale Computing Project (ECP-WDMApp and ECP-CoPA)

Princeton Collaborative Research Facility (PCRF) for LTP

- Established in 2019 from low-temperature plasma (LTP) labs at PPPL and Princeton MAE
- **Supported by the Department of Energy, Fusion Energy Sciences (~$1.5M / year)**
- Mission: to provide state-of-the-art research capabilities and expertise to advance understanding and predictive control of LTPs with focus on:
  - Plasma interactions with liquids, solids, nanoparticles
  - Transport and collective phenomena in LTPs
  - LTPs in modern applications: materials, health, environment, aerospace, etc.
- Expertise: plasma physics and modern applications, advanced diagnostics, computation







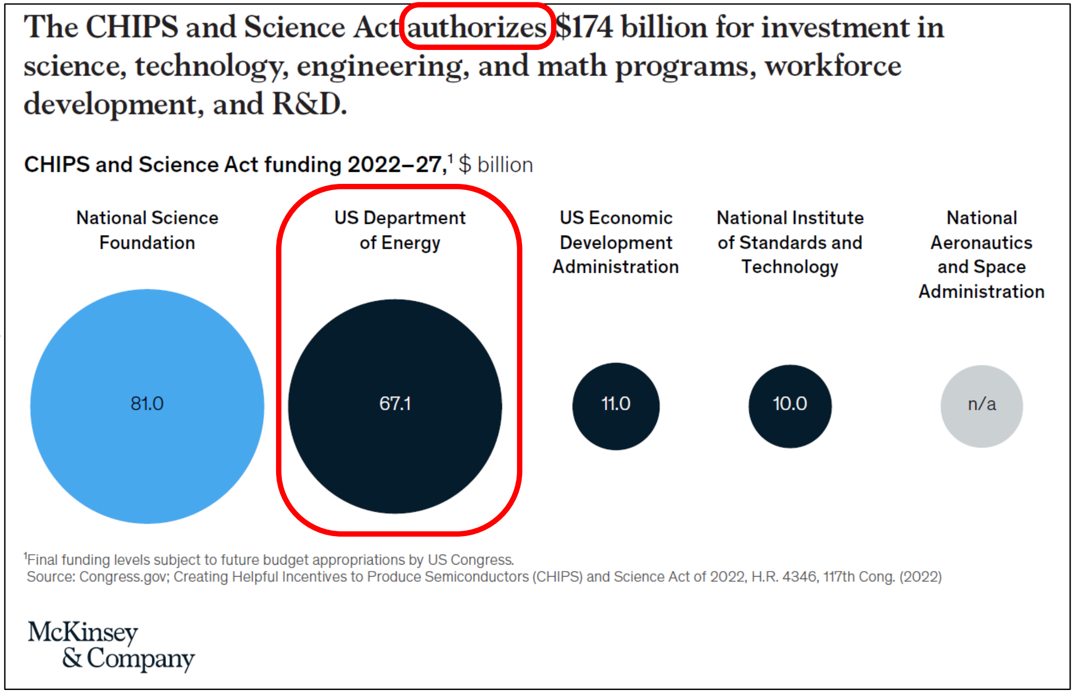
Plasma Plays Key Role in Microelectronics, U.S. Economy

Annual revenue:

- Electronics ~$2T
- Semiconductors ~$0.6T
- Wafer fab equipment ~$50B
- Plasma equipment ~$15-$20B
  - ~ 40-45% of 450-900 steps plasma-related


Forbes

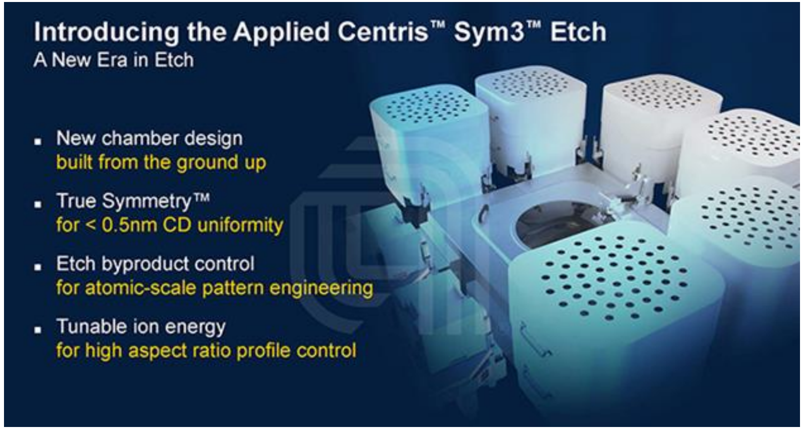
How Semiconductor Shortages Have Taken A Chip Out Of The Global Supply Chain



Diagnostic and Experimental Research with Applied Materials

- Respond to a growing demand for noninvasive optical diagnostics of processing plasmas in state-of-the art industrial reactors:

- Etching, CRADA (open research) and SPP (proprietary) with AMAT, Santa Clara, CA

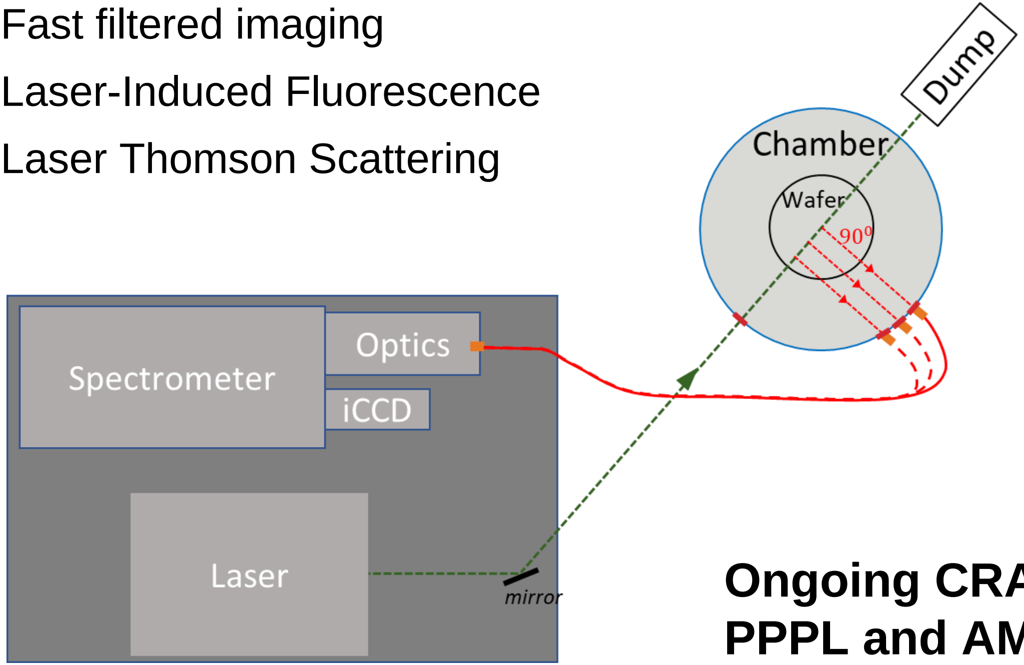


- Ion implantation, SPP (proprietary) with AMAT/Varian, Gloucester, MA

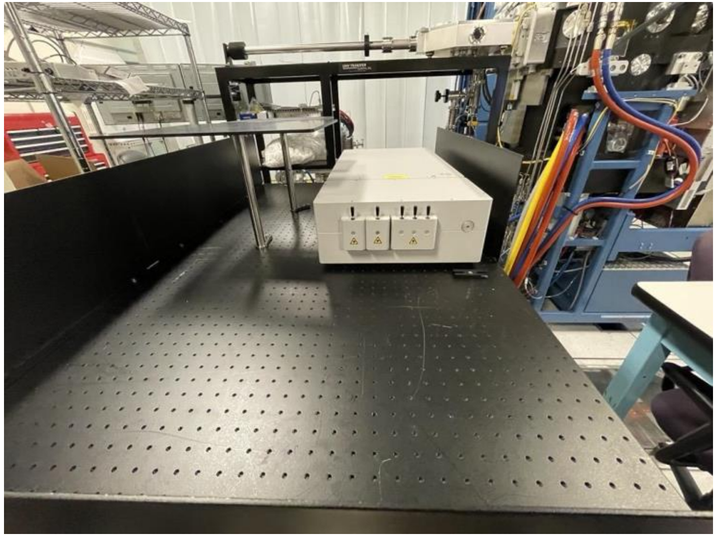
VIISta® 900 3D implanter

PPPL Diagnostics at Applied Materials, Santa Clara, CA

- Optical emission spectroscopy
- Fast filtered imaging
- Laser-Induced Fluorescence
- Laser Thomson Scattering



- Laser diagnostics setup at AMAT



Ongoing CRADA and SPP experiments by PPPL and AMAT teams at the AMAT site

Research on Ion Implantation (proprietary and open)

- Ion implantation is a critical process in multistep microchip fabrication.
- Ion beam uniformity depends on the ion beam quality affected by plasma in ion source.
- Integrated experimental (PPPL) and modeling (AMAT/Varian) efforts.
- AMAT/Varian SPP with PPPL was motivated by PPPL relevant existing expertise on ExB and Hall thruster physics (http://htx.pppl.gov).


PPPL Hall Thruster

Modeling needs for plasma reactors in microelectronics

PlasmaPro 100 Cobra ICP RIE Etch

Tactras-UDEMAE plasma etch system

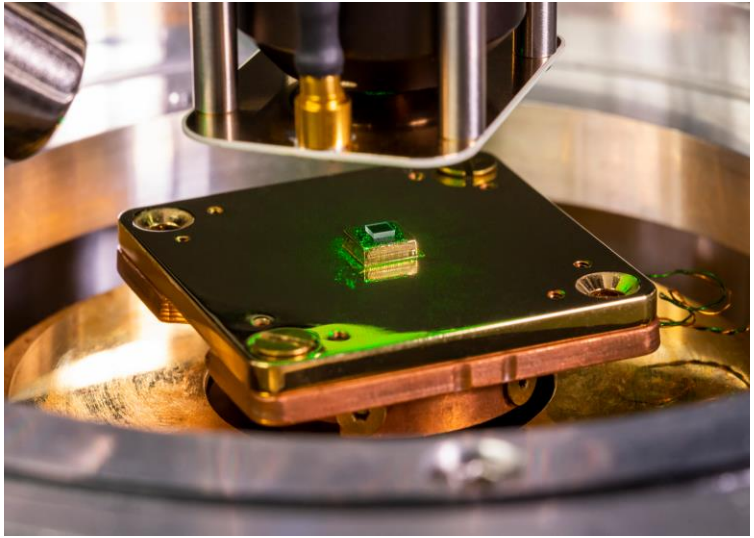
Industry invests $billions in large, complex machines for chip manufacturing (etching, deposition)

Any insights on plasma and chemical processes can provide competitive advantage

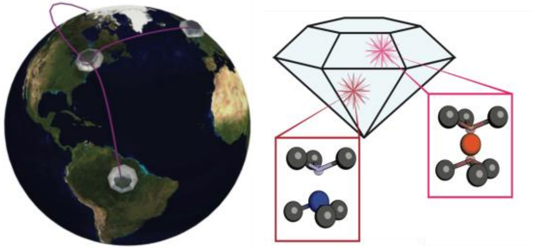
PPPL: New computational tools

- Fully **kinetic treatment** of plasma reactors
- Complete reaction pathway of chemistry in plasma and at interface with surface
- Novel computational tools that are easy to use and give fast turnaround

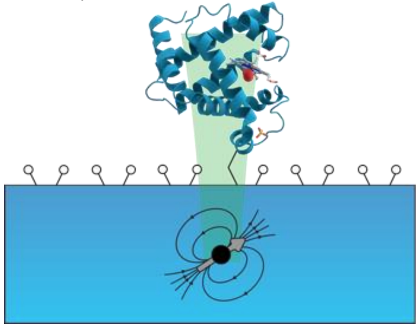
Quantum Diamond: A QIS platform



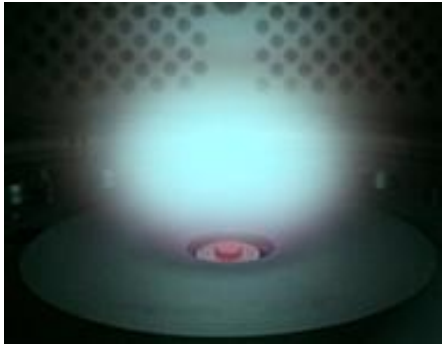
Quantum networks



Quantum sensors



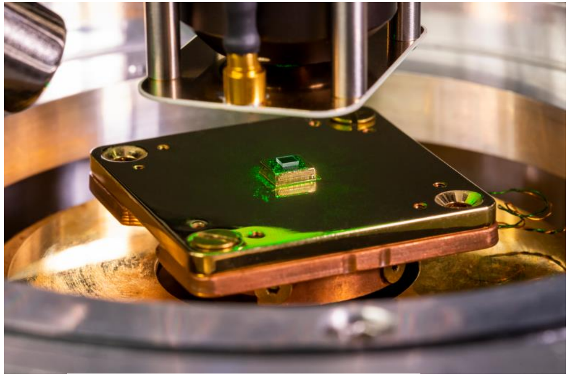
Plasma-enhanced chemical vapor deposition (CVD) is only way to grow quantum diamond

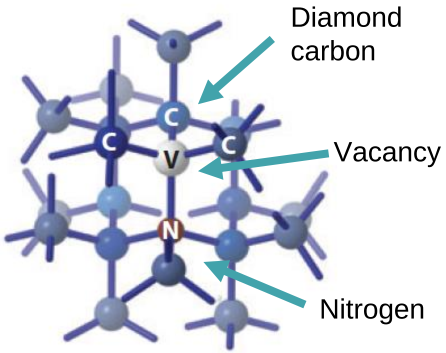


Nathalie de Leon
Princeton University

Alistair Stacey
RMIT and University of Melbourne

Quantum Diamond: A microelectronics QIS platform





Quantum Diamond QIS platform

- Solid state spin qubits
- Optically and electrically addressable
- Semiconductor with room-temperature coherent quantum states
- Charge state control required via electronic co-doping

Diamond Electronics

- Existing research in diamond electronics (high power / frequency)
- n-type and p-type electronic dopants available (both deep)

Future Diamond Opportunities

Micro-electronics

- Diamond Electronics for high power transistors
  - Sustainability power needs require increased use of fast, solid-state, high power current switching
  - EVs, smart grid switches, power conversion with renewable sources (DC -> AC)
- Thermal spreaders
  - Diamond has an extreme thermal conductivity and is being actively investigated for thermal management in non-diamond semiconductor systems (e.g. diamond-on-GaN)
- Heteroepitaxial wafer-scale growth
  - Development of large-area single-crystal diamond for industrial scale-up of electronics, quantum devices
- Diamond plates for ballistics
  - Replacement of SiC and C_3N_4 ballistics protection material
- Fusion fuel capsules
  - NIF fuel cell capsules use diamond ablators, no US source for these

New PPPL Department – Applied Materials and Sustainability Sciences

Led by Princeton University Professor Emily A. Carter (Mechanical and Aerospace Engineering), former dean of the Princeton School of Engineering and Applied Science

Staffing up:

- Hiring researchers in QIS
- Appointed interim leadership in Microelectronics, QIS, Solar Geoengineering, and Electromanufacturing Science
- Aim to add joint faculty + research staff in each area as grow programs

Microelectronics and QIS

- Established PPPL-PU steering committee to prepare for SC call for microelectronics research center proposals (in FES FY24 budget)
- PPPL/PU partnering on DOD MicroElectronics Commons (QIS)

Electromanufacturing

- PU/PPPL plasma-assisted cement production proposal to EERE
- Multiple EERC pre-proposals, with NREL, ORNL as key partners

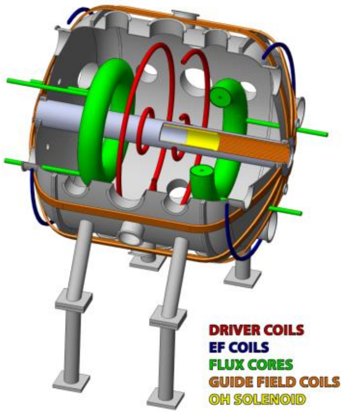
Solar Radiation Management

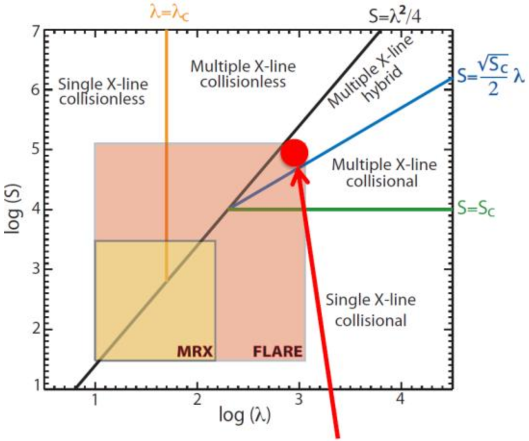
- Together with Simons Foundation, developing $10M/yr @ 5+ yrs international collaboration on aerosol-light-cloud science

Mission 3: Understand Plasma Universe

- Facility for Laboratory Reconnection Experiments (FLARE)
- Extreme plasma astrophysics
- High-energy density laboratory plasma physics

Facility for Laboratory Reconnection Experiments (FLARE)

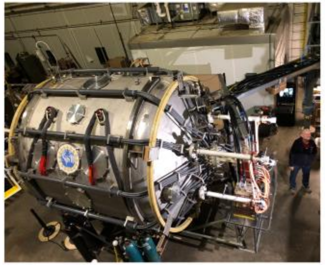




$$S = \mu_0 L_{CS} V_A / \eta_S; \quad L_{CS} = L/4; \quad \lambda = L/\rho_S$$

Design target for FLARE to access all reconnection phases

FLARE at Princeton



FLARE at PPPL

FLARE Mission:

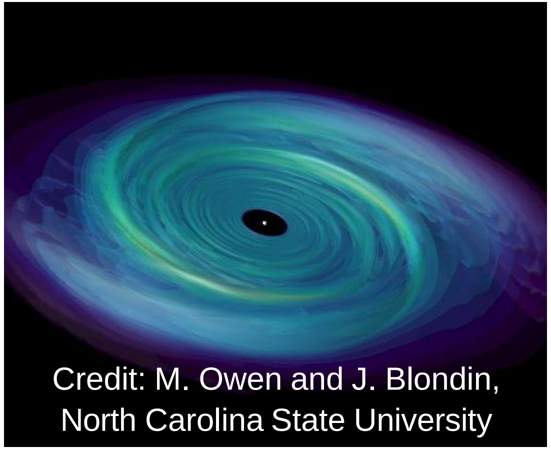
- Study magnetic reconnection in regimes directly relevant to space, solar, astrophysical, and fusion plasmas
    - Use staged upgrades to access new “multiple X-line” reconnection regimes not currently accessible in existing devices
- Provide collaborative research facility for domestic and international users

FLARE Status

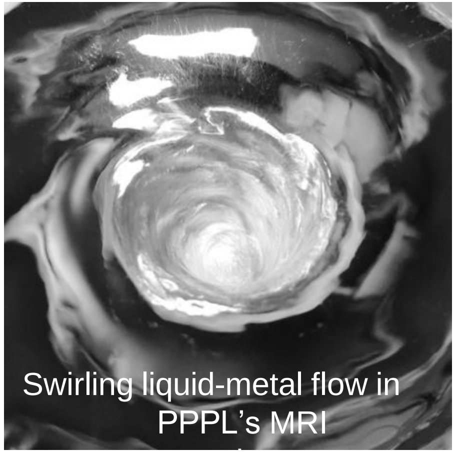
Several stops/starts, rebaselined last August, project resumed in October, will finish in 2024

- Vacuum pump system mechanical is complete
- Drive coils construction ramping up
- Capacitor bank assembly substantially complete
- Platform fire protection system substantially complete
- Interlock system is progressing with installation contract awarded, electrical safety completed review of installation procedures.
- Control Room furniture is in place and the Wall Display and A/V equipment are installed
- Commissioning meetings initiated
- Overall scope 79% complete

PPPL liquid metal experiment "MRI" investigating Standard Magneto-Rotational Instability (SMRI)

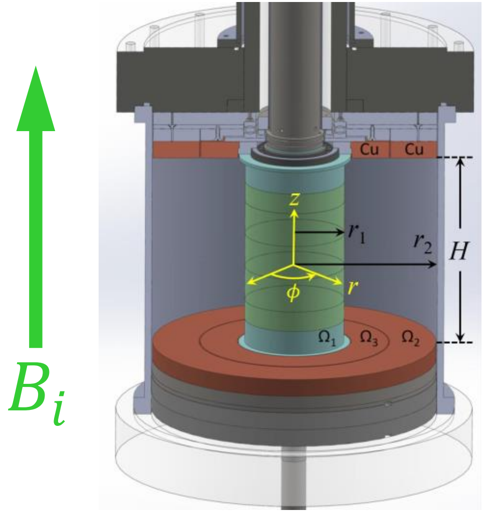

Credit: M. Owen and J. Blondin, North Carolina State University

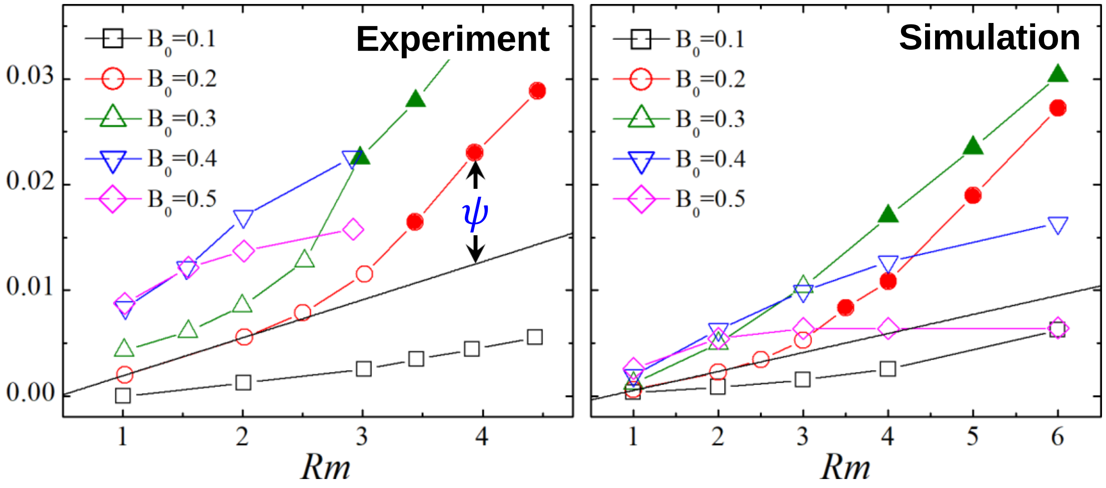
*Balbus and Hawley, *Rev. Mod. Phys.* **70**, 1 (1998).


Swirling liquid-metal flow in PPPL's MRI

- An accretion disk consists of a compact central astronomical object, and a material flow that continuously spirals inward.
- The swirling material flow is usually ionized, which could be destabilized by the magnetic field in accretion disks – a theorized MHD process called SMRI*
- SMRI is believed to be responsible for the turbulence generation in the disk plane that largely prompts the accretion process to the rate observed by telescopes.

New: First convincing evidence of axisymmetric SMRI





- Galinstan, a room temperature liquid metal is used as the working fluid.
- Multiple Hall probes of high precision (~0.5 G) installed at the inner cylinder surface
- The magnetized residual Ekman circulation causes a linear increase of B_r at $R_m \lesssim 2.5$ for all B_0.
- SMRI manifests as a ***super-linear increase*** in the B_r -R_m relation, $\psi > 0$ characterizes its strength

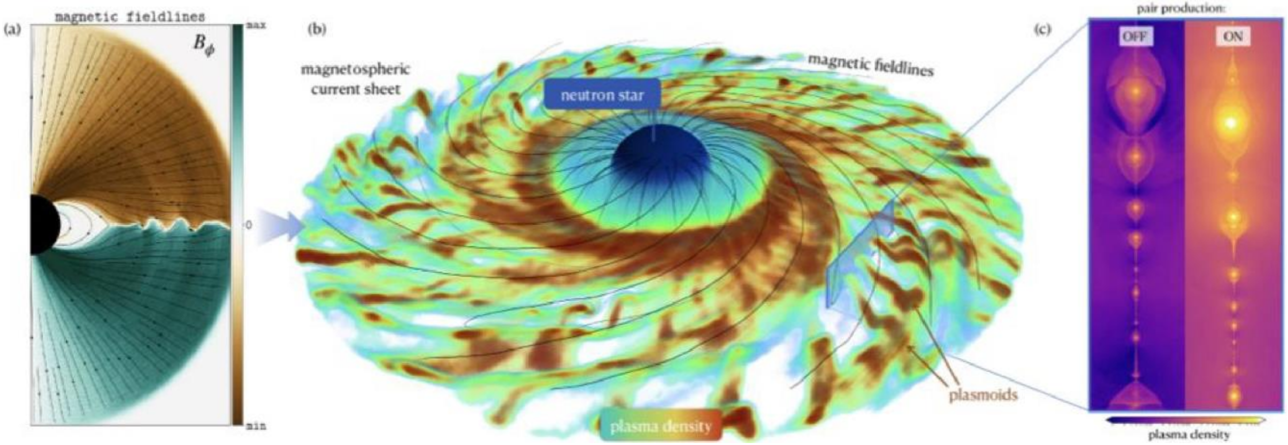
Yin Wang, et al. Phys. Rev. Lett. ***129****, 115001* (*https://doi.org/10.1103/PhysRevLett.129.115001*)

Plasma physics fundamental to multi-messenger astronomy

Black holes, gravitational waves, gamma ray bursts, neutron star mergers

What we observe reflects a wide range of plasma phenomena

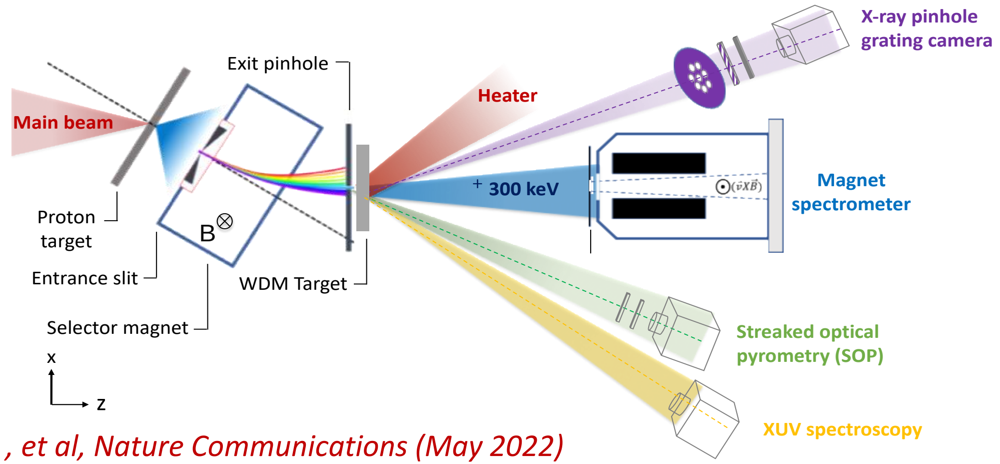
This is a pulsar simulation showing the critical role of **kink** instabilities and magnetic reconnection in a highly relativistic setting



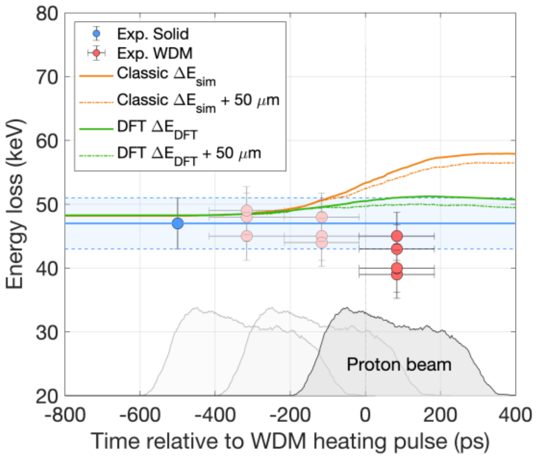
- PPPL has launched a project in new Computational Sciences Department led by Prof. Bill Dorland (UMD) to extend exascale, kinetic plasma simulation knowledge to highly relativistic astrophysical systems, which are very well-diagnosed.

Novel low-velocity proton transport and stopping power measurements achieved in Warm Dense Matter regime

- Warm Dense Matter (WDM) regime, near solid density with T ~ 10 eV, is extremely challenging theoretically as it behaves between classical plasma and condensed matter, with quantum degeneracy effects and strong Coulomb coupling.
- Proton stopping in WDM has important implications for ICF and IFE
- First experiments on proton stopping power at low velocity projectile ratio show significant deviations from classical stopping, closer to density functional theory



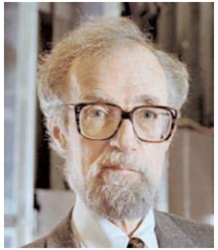
S. Malko , et al, Nature Communications (May 2022)



PRINCETON PLASMA PHYSICS LABORATORY

PPPL Future

Fusion Research and Technology Hub (FuRTH) Test Cell ready



Harold P. Furth (1930-2002)
PPPL Director who brought
Tokamak Fusion Test Reactor
(TFTR) to PPPL in 1980s →
10MW fusion power 1994

TFTR test cell cleared and tritium handling system removed

The size of the FuRTH test cell could support multiple experiments and provide a platform for partnerships with fusion industry.

Future building: Princeton Plasma Innovation Center (PPIC)

View of PPIC from west (present Theory parking lot)

New collaboration spaces including remote collaboration, visualization, and office spaces

Additional small-bay lab spaces for NSTX-U diagnostics, actuator development, collaborators

New medium-bay lab spaces for large fusion diagnostics, microelectronics, sustainability

Thank you for listening!

Any questions?

Backup

NSTX-U Recovery Project has 4 Key Performance Parameters

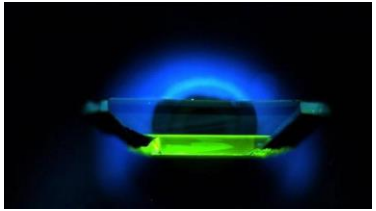
…to demonstrate required capabilities of systems modified by Recovery

1. **Coil alignment:** The inner-Toroidal Field coil axis shall be aligned to the PF-5 lower coil mutual axis with an accuracy bounded by a straight line through the [shift, tilt] points [0.0 mm, 6.0 mrad] and [6.0 mm, 0.0 mrad]
2. **Graphite tile bakeout:** A bakeout will be conducted in which graphite PFCs shall achieve a temperature of at least 260 degrees Celsius
3. **Integrated coil test:** Without plasma, the magnetic field coils will be pulsed using OH/TF/PF waveforms expected for a 1.4MA, 0.85 Tesla, 4 second plasma with 2 second plasma current flat-top
4. **"First plasma":** An ohmically-heated discharge shall be produced with plasma current greater than 50,000 Amperes at a toroidal magnetic field of greater than 1,000 Gauss

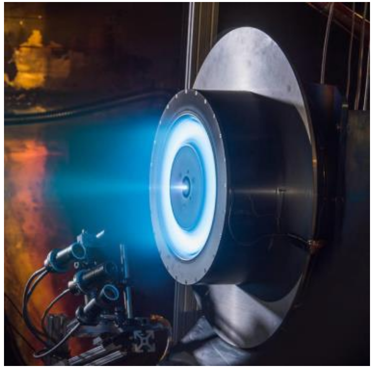
Low-temperature plasmas (LTP) increasingly vital to US economy

Plasma reactors for etching and deposition for **microelectronics** applications

Quantum Information Science (quantum diamond)



Sustainability (e.g. methane pyrolysis for production of hydrogen, solid carbon)



And more applications: propulsion, nanofabrication, plasma-wall interaction in tokamaks, etc.

Industrial partners

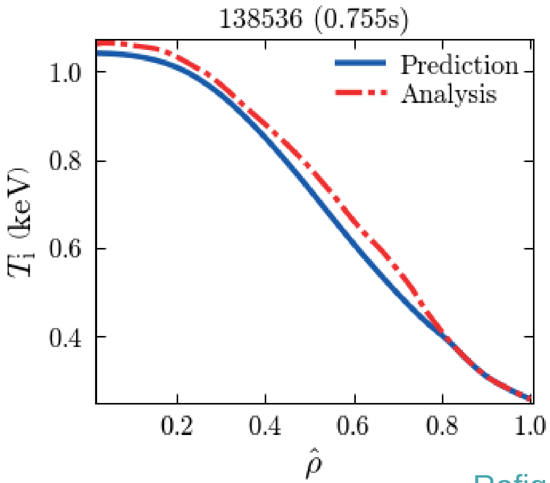
SPP: Strategic Partnership Project (Proprietary Agreement)
CRADA: Cooperative Research & Development Agreement

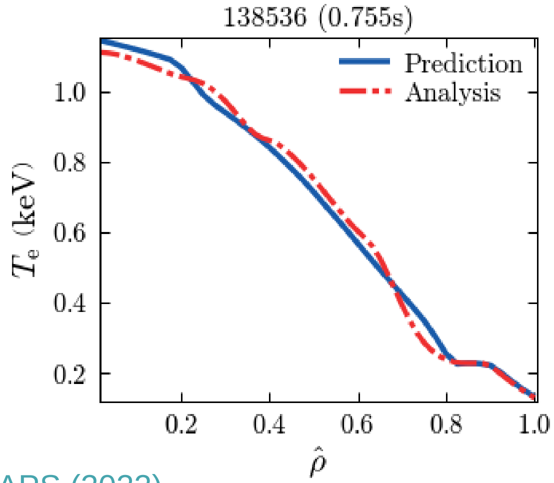
- Applied Materials (AMAT)
  - 2 CRADAs and 1 SPP (experiment)
- Lam Research
  - CRADA
- Samsung
  - SPP
- General Electric
  - ARPA-E
- Exxon (sustainability)
  - SPP (future: Princeton direct funding)

Multi-Mode Model (MMM) reproduces profiles in high-β, low-ν NSTX discharges

- Includes microtearing mode (MTM) model required in higher beta discharges [Rafiq 2016, 2022]
- **Future: explore broader validity, confinement projections to NSTX-U & FPP**

T_i & T_e prediction using Multi-Mode Model (MMM)

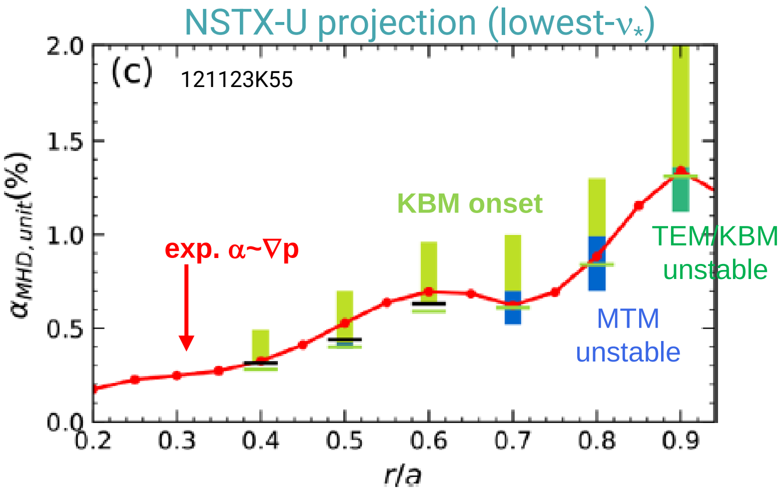




Rafiq, APS (2022)

High-β discharges predicted to be very close to linear kinetic ballooning (KBM) threshold deep into the core

Normalized pressure gradient ($\alpha \sim \nabla p / B_\theta^2$)



Clauser, PoP (2022)

- Profiles in high-β, low-ν NSTX and NSTX-U projections generally far from ITG onset
  - Low-A, high-β equilibrium is stabilizing, as predicted long ago [Rewoldt, 1996; Kotschenreuther, 2000, …]
- Future: develop and validate KBM-limited profile predictions [GA, PPPL]
- Compare with similar conditions at conventional-A (e.g. DIII-D and EAST high-β_{pol} scenarios for FPP

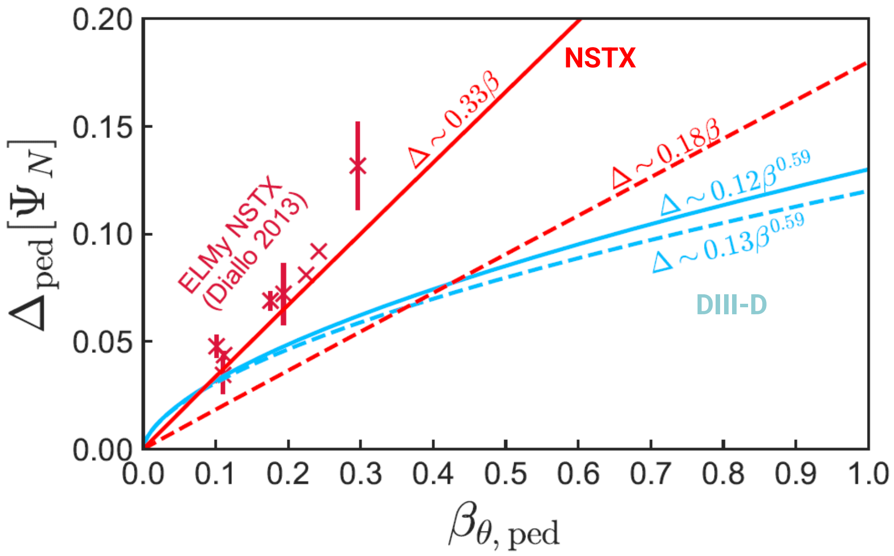
Developed gyrokinetic-based prediction of pedestal width-height scaling, recovers linear scaling for NSTX ELMy H-mode

- Directly using linear gyrokinetics (CGYRO) to predict KBM-limited pedestal height
  - EPED-like workflow developed to consistently vary pedestal profiles, bootstrap current, global equilibrium
- Scaling stronger than that using ideal infinite-n ballooning stability (BALLOO)
- Recovers weaker scaling at conventional-A

<u>Ongoing work</u>

- Validate over broader dataset (NSTX & others)
- Integrate non-ideal P-B + gyrokinetic analysis into a predictive pedestal structure model, make projections for NSTX-U and other devices

Pedestal width vs. height predicted from KBM



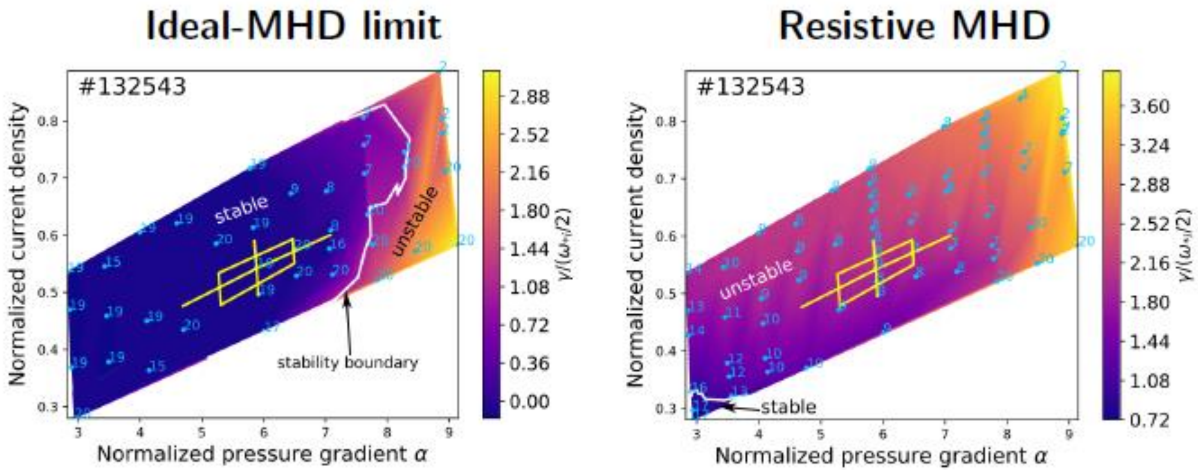
Parisi, APS (2022)

ELMy discharges most consistent with resistive, not ideal, peeling-ballooning (P-B) stability

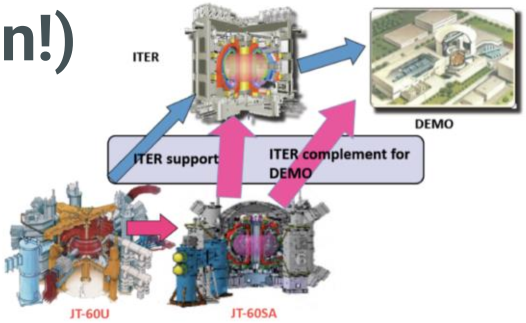
- Resistivity matters for NSTX ELMy discharges near kink-peeling boundary (using linear M3D-C1)
- Impact of resistivity varies across experiments (tested for NSTX, MAST, DIII-D)
  - Most correlated with magnetic shear → possible role of tearing mode physics
- Ongoing work to project whether or when non-ideal P-B important for NSTX-U
- Ongoing work to explore nonlinearly saturated pedestal modes in ELM-free scenarios

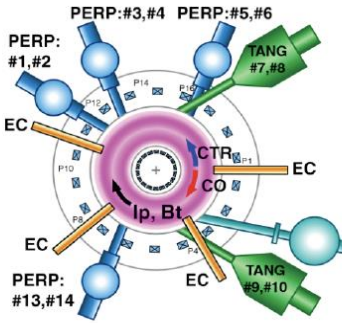
Peeling-ballooning growth rates (M3D-C1)

Kleiner, NF (2021, 2022)

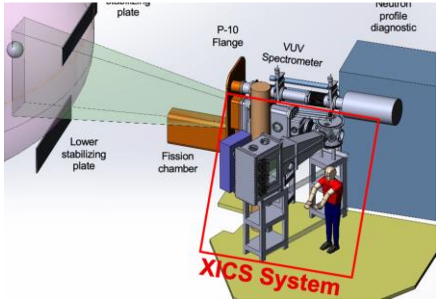


Collaborations: Design, build and commission an x-ray crystal spectrometer for JT60SA (thanks UW-Madison!)

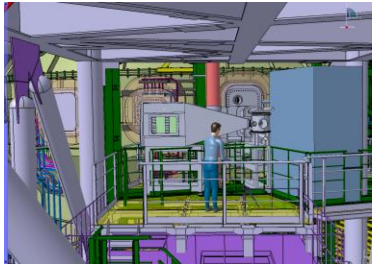


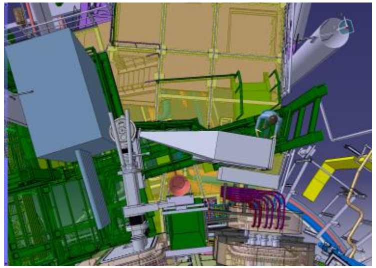


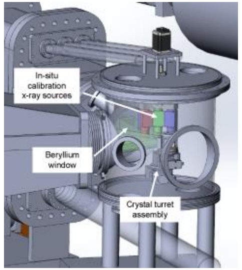
- **JT60-SA will be the most flexible and powerful tokamak in the world before ITER-DT [41 MW]**

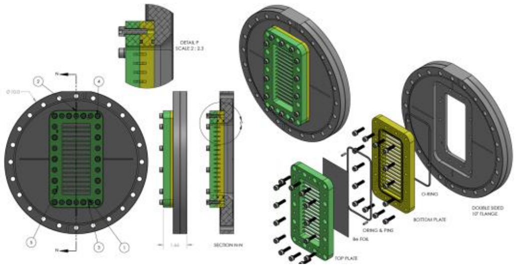


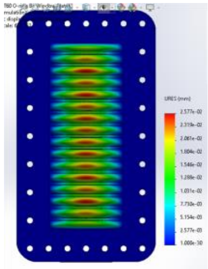
- PIs: Luis Delgado-Aparicio and Masa Ono
- Procurement, construction, calibration and commissioning: FY22-24
- $6M in funding from DOE – design and CAD led/greatly aided by UW
- PPPL support facility under development

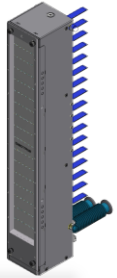












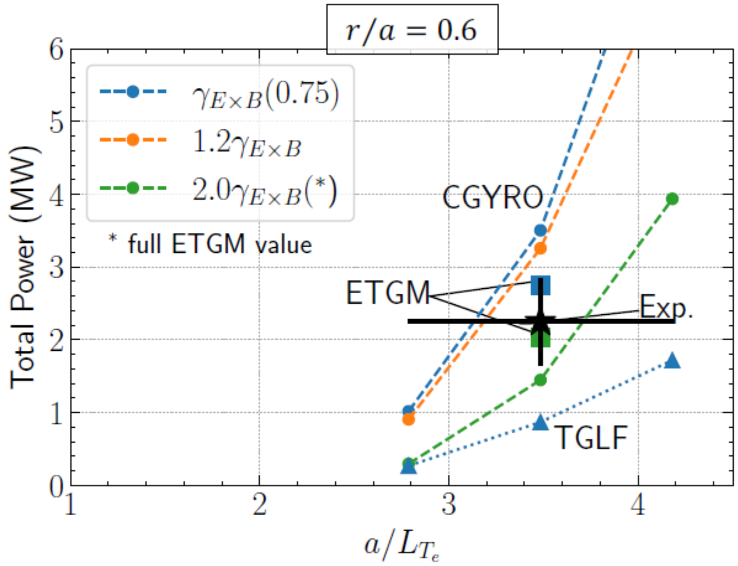
Have begun qualifying reduced transport models directly against higher-fidelity nonlinear gyrokinetic simulations

- ETG electron heat flux from models (TGLF, Lehigh ETGM) "close" to nonlinear gyrokinetic simulations

Ongoing work:

- Expand validation over broader dataset & other transport mechanisms [Lehigh, GA, ORNL]
- Update saturation models that span aspect ratio
- Quantify finite-ρ_*, non-local effects [Sharma, 2022]

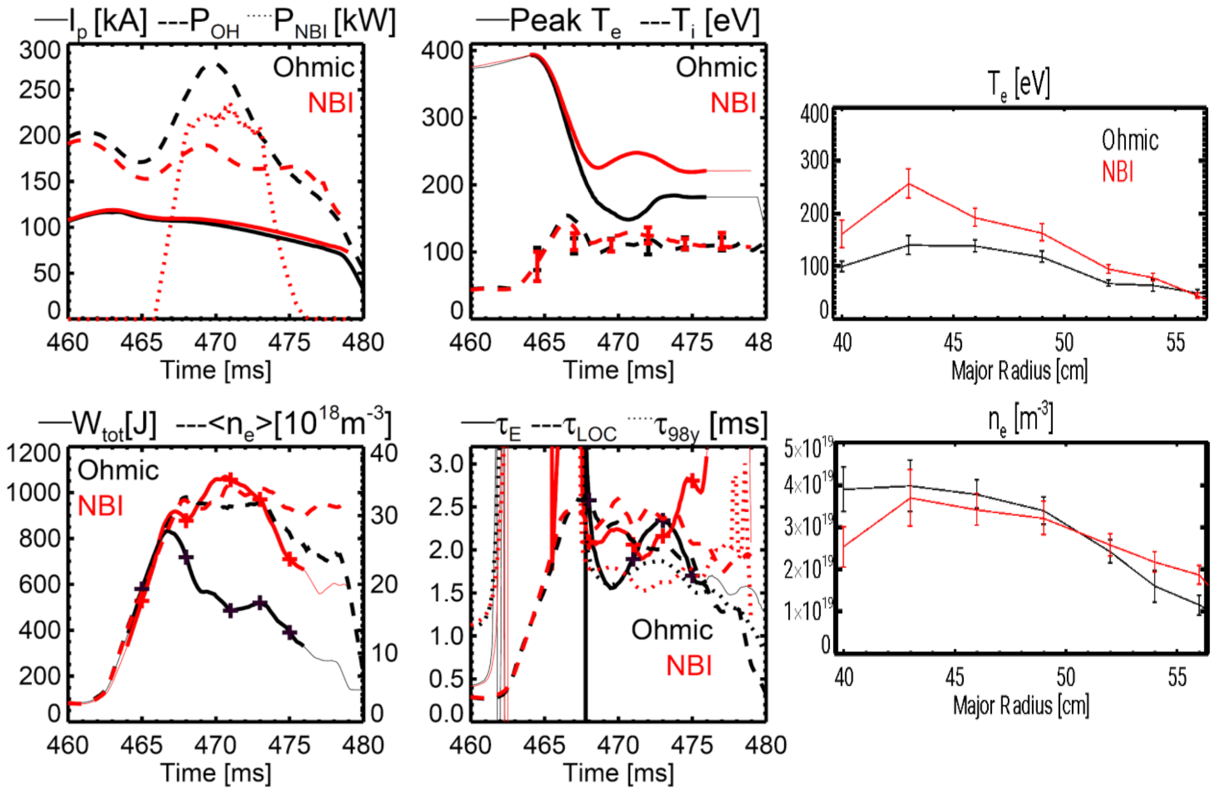
Electron heat flux from ETG (gyrokinetic compared to model)



Clauser, APS (2022)

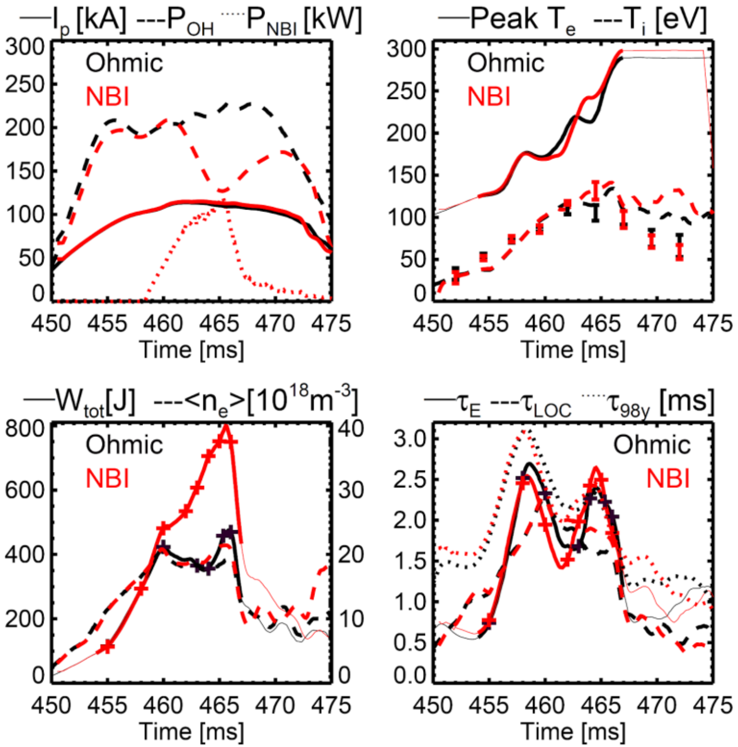
LTX-β progress – confinement scaling with NBI

- Clear increase in central T_e and doubling of W_{tot}
- NBI confinement time ~same as ohmic value

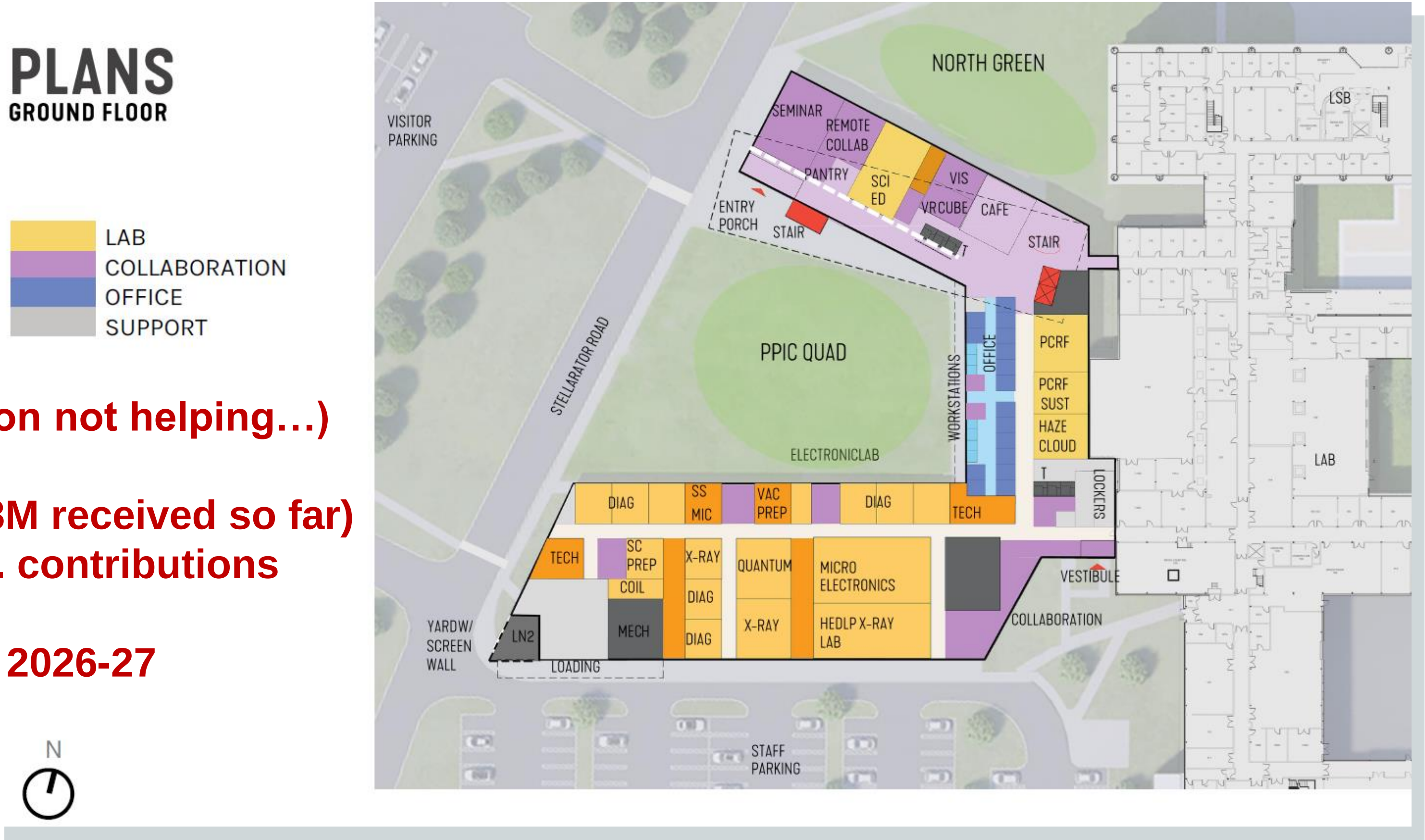


LTX-β progress – flat electron temperature profiles

- Weaker NBI heating due to lower n_e and I_P → higher NBI losses
- Higher $T_e(0)$ → slowing down time > NBI duration → need upgrade
- NBI confinement time again similar to ohmic value



PPIC overhead view



~60k GSF (inflation not helping…)

~$100M TPC ($28M received so far) + Princeton Univ. contributions

To be completed 2026-27