Develop the Basis for Plasma Material Interface (PMI) Solutions for FNSF

FESAC Strategic Planning Panel

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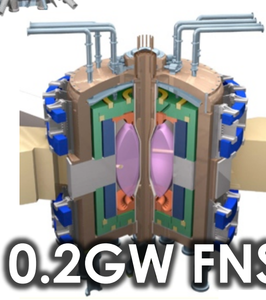
Divertor/PFC Challenge: Reliably Dissipate Heat and Particle Flux in a GW-scale Fusion Reactor

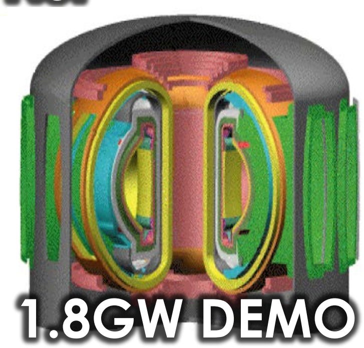
Prior studies show gaps

- **Predictable boundary plasma control** to bridge the transition from the hot fusion core to material surfaces.
- **Qualified plasma-facing components** designed for the expected reactor environment
- **Fully integrated solutions** for core, boundary, and components producing high fusion gain.

2014 2025 2050

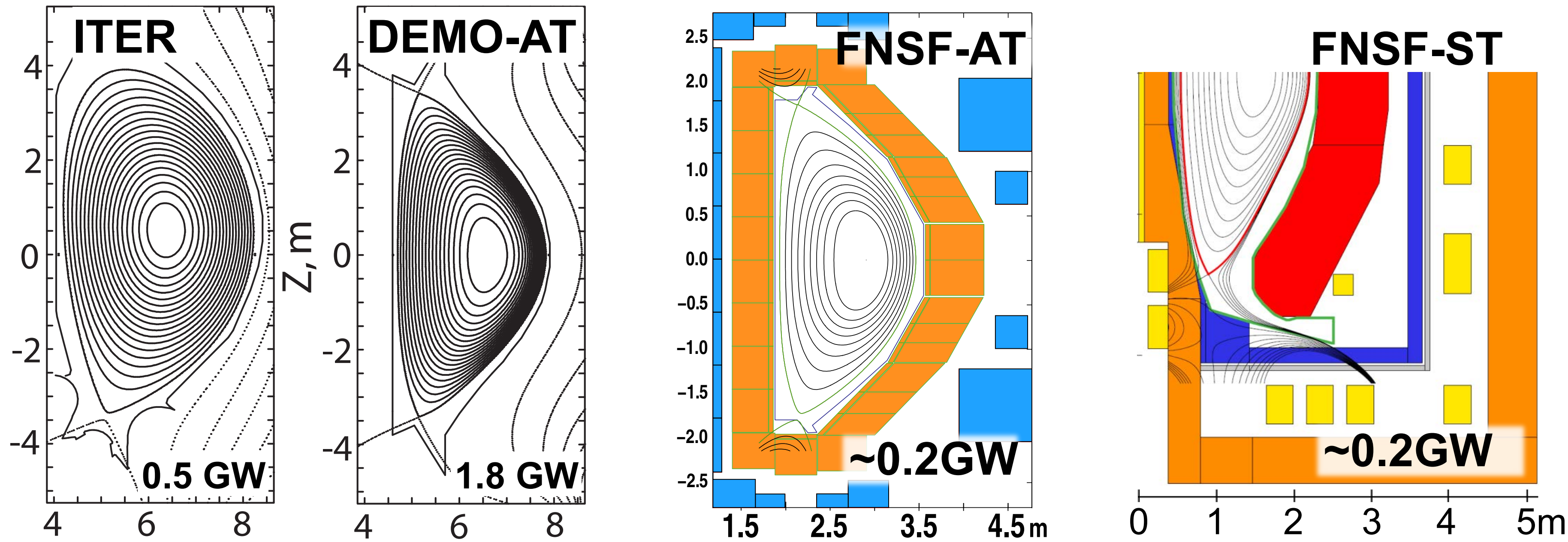
US Program

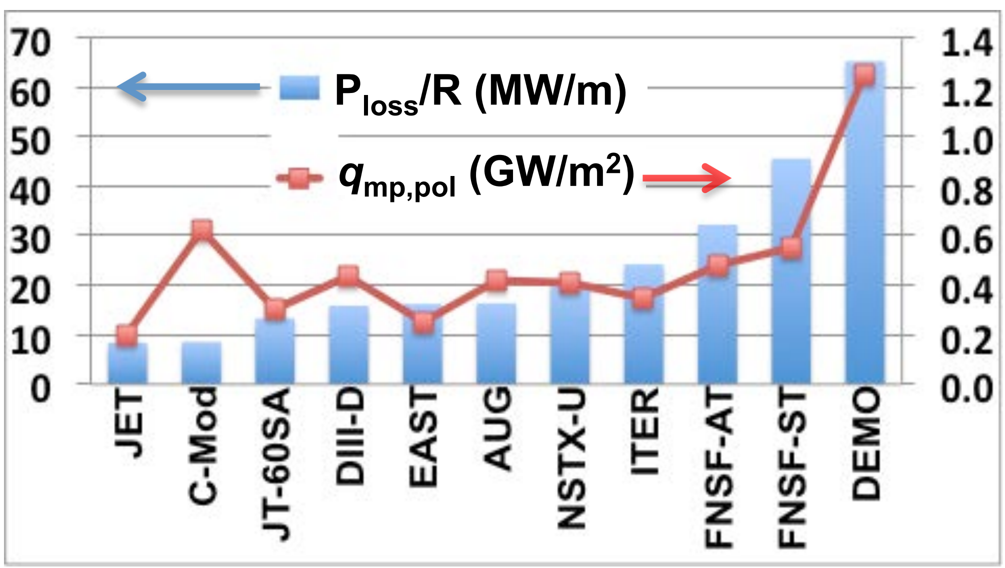




Starting FNSF design by 2025 increases urgency to resolve the PMI challenge

FNSF and DEMO-Scale Tokamak Design Studies Inform Research Needs for Plasma Material Interface Solutions





Divertor target heat flux

$$q_{target} = \frac{(1-f_{rad})P_{loss}}{2\pi\, R_{target}\, \lambda_{q,mp}\, f_{exp}}$$

$$P_{loss} = P_{CD} + 0.2 \times P_{\alpha}$$

- Physics
- Design/Engineering

Solution-based Science Initiatives Can Provide A Reasonable Basis for Designing the FNSF Divertor

1. **Develop robust boundary-plasma solutions to mitigate PMI challenges**
    a. Comprehensive measurements and coordinated multi-machine experiments
    b. Upgrades to existing tokamaks (Diagnostics, divertors, power)
    c. Boundary simulation centers with analysts tightly coupled to experiments

2. **Design and Test Candidate PFC Materials (partner with BES)**
    a. Develop new materials and materials technology [simulation + testing labs]
    b. Materials exposure in linear plasma facilities (existing US and international)
    Radiation-damage evaluation (access needed to neutron sources)
    c. Plasma material interaction experiments in tokamaks (existing US and international)

3. **Pursue Core-Edge Physics and Operational Integration**
    a. Test large-area samples of candidate PFC materials at realistic operating temperatures in high-performance tokamaks
    b. Use SC long-pulse experiments to evaluate steady-state PFC operation [international]

Consistent with ReNeW Theme 3: Taming the Plasma Material Interface

Boundary-plasma Control Requires Edge Radiation and Divertor Detachment to Reduce Surface Heat Flux, Erosion

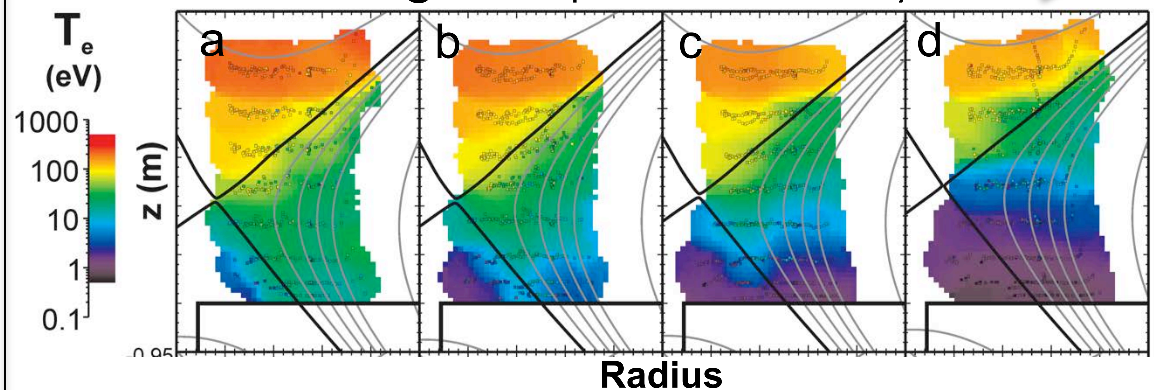
Boundary impurity radiation reduces P_{SOL}

usually small in present exps

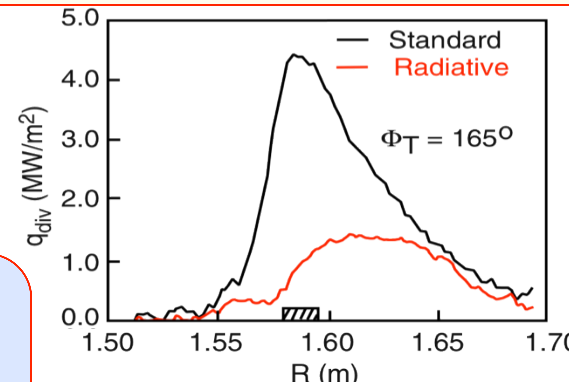
Divertor radiative cooling enables recombination

Recombining detached divertor (T_e<2eV)

Increasing core plasma density →



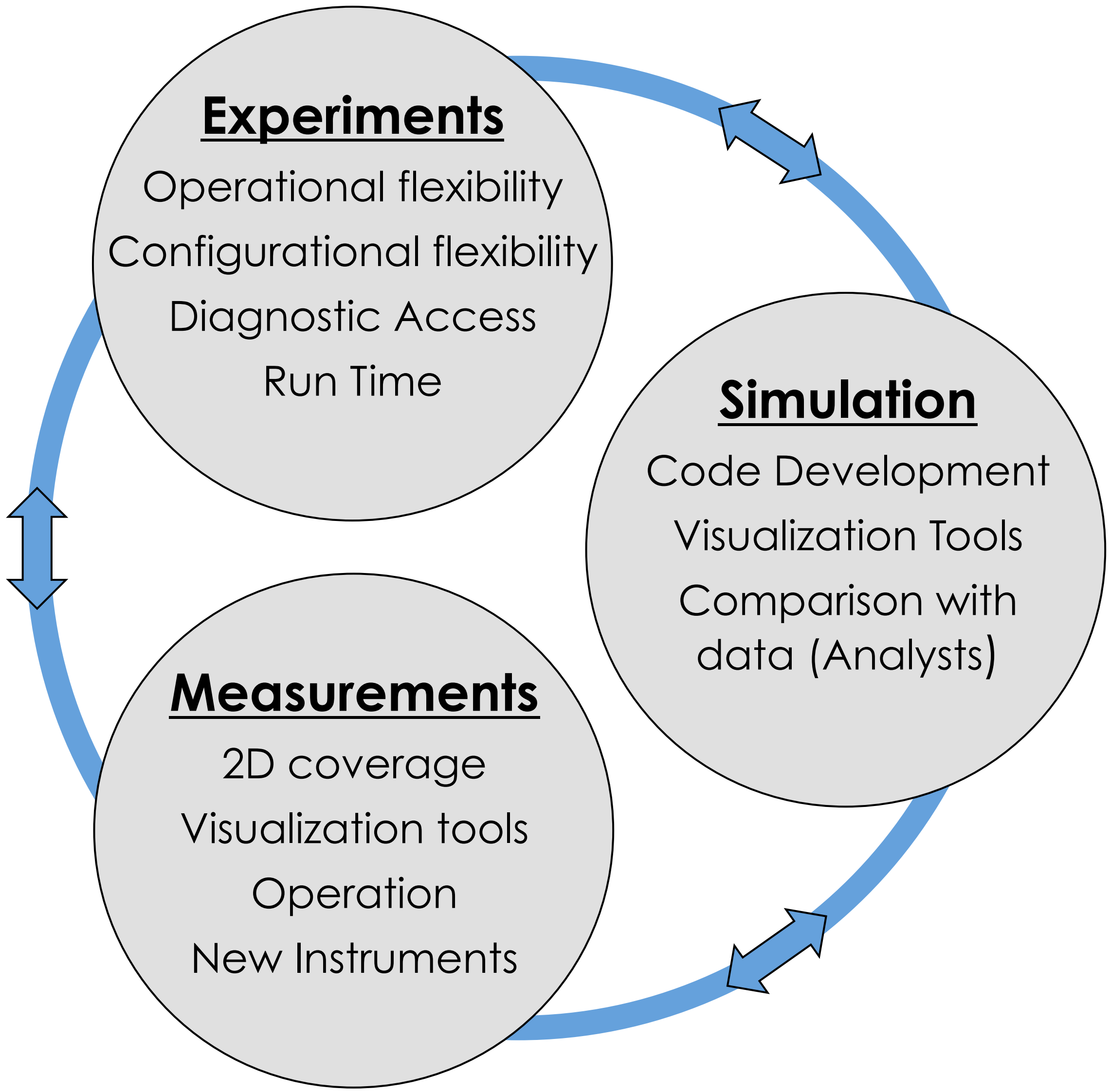
Strongly reduced divertor heat flux



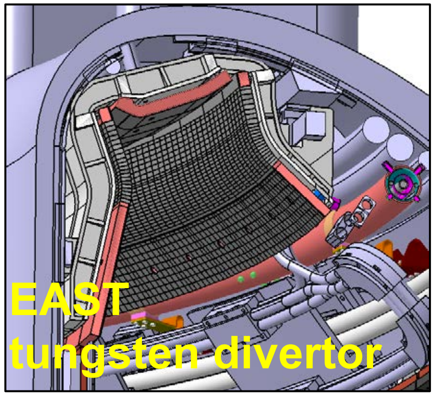
- **Basic physical processes identified**
- **Validated 2D predictive model needed**
- **Role of geometry, boundary conditions uncertain**
- **Extend to higher power density, radiation fraction**

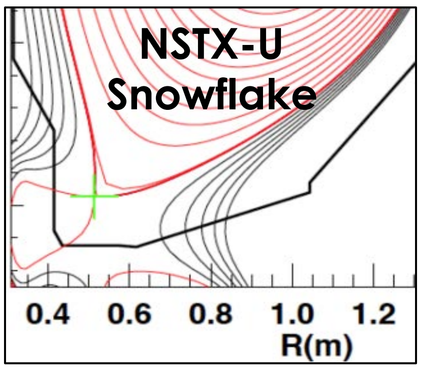
Bndry Plasma Solutions

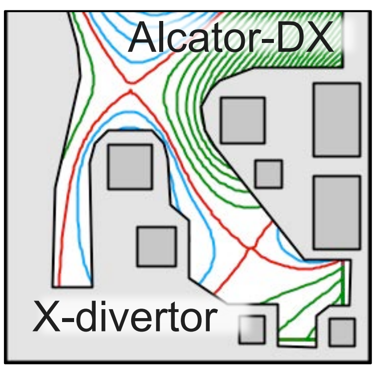
Developing Boundary-plasma Solutions Iteratively Links Facilities – Measurements – Simulation



It Is Imperative to Develop Boundary-plasma Solutions Using Non-Nuclear Confinement Facilities







Experiment

Flexible operation

Fault tolerant

Flexible configuration

Routine access

Simulation

Match trends

Match values

Add new physics

Propose new exps.

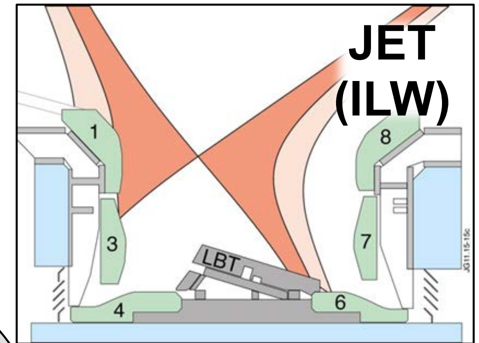
Measurements

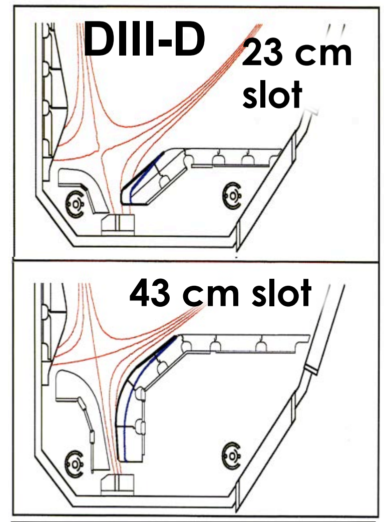
Manageable costs

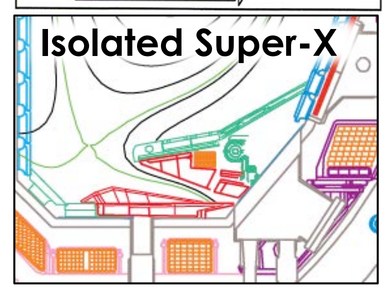
Broad coverage

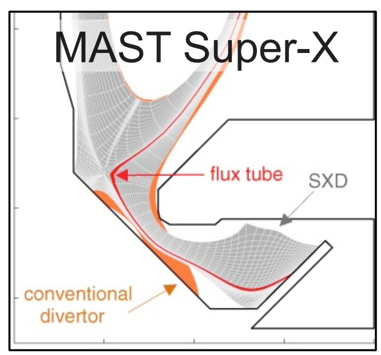
Easy Access

Maintainable





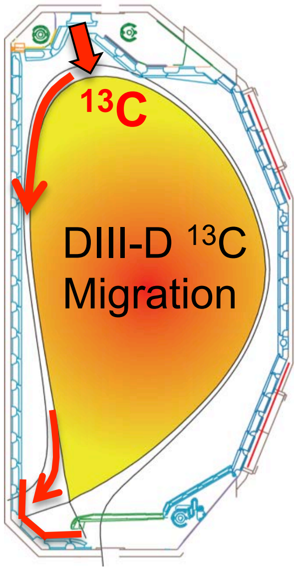


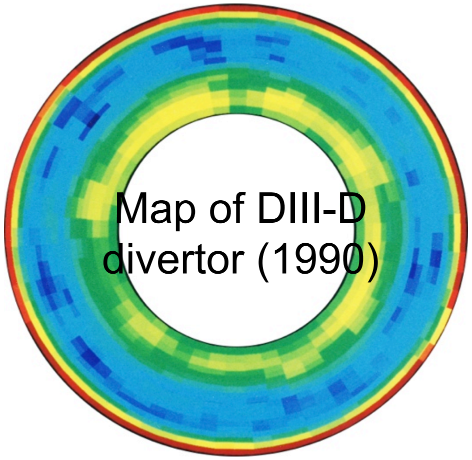


Fusion Program Must Engage the Materials Science Community to Develop Materials, Processes, Components

- **Existing fusion PFC materials have known problems (W, C, Be, Li)**
  - Sputtering and long-term material migration
  - Core plasma sensitive to high-Z contamination
  - Transients, Tritium retention, neutron damage
- **High-Z divertor materials may work (cold detached divertor plasma)**
- **Divertor and first wall material surfaces will be at high temperature(~900C)**
- **ITER first-wall not designed to meet steady-state reactor requirements**
- **New Materials, Components, Mitigation Techniques are required**

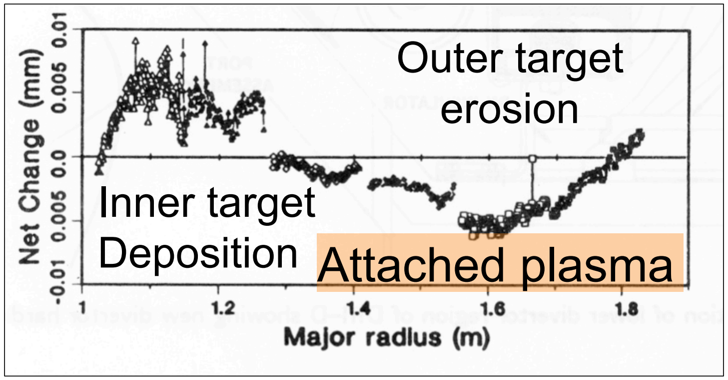
SOL flow carries impurities to inner target





Sputtered metals end up on inner divertor (~10^4s)

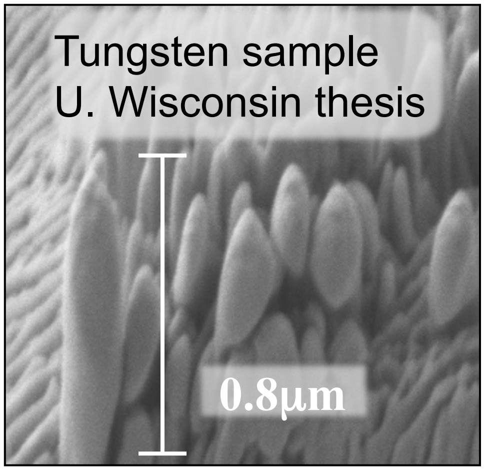
Divertor carbon migration (~10^4s)



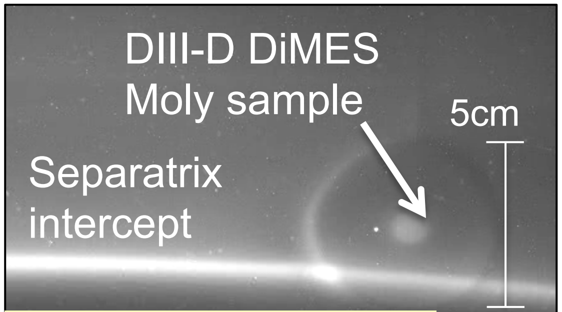
Develop Materials

Relevant Time, Temperature, and Spatial Scales Motivates Targeted Materials Research In a Wide Range of Facilities

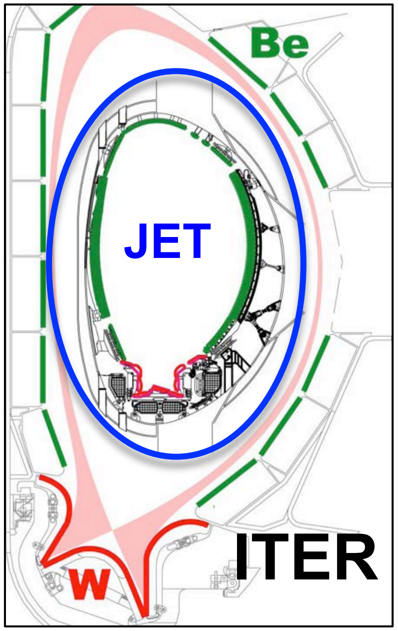
τ_{SOL}	τ_E, τ_{surf}	$\tau_{particle}$	$\tau_{Resistive}$	$\tau_{Blanket}$	$\tau_{migration}$
0.1ms – 10s	~ 1s – 10s	~ 100s	~ 300s	~ 10^6s	~ 10^7s



Zenobia, Garrison, Kulcinski
JNM, **425**, 83–92 (2012)



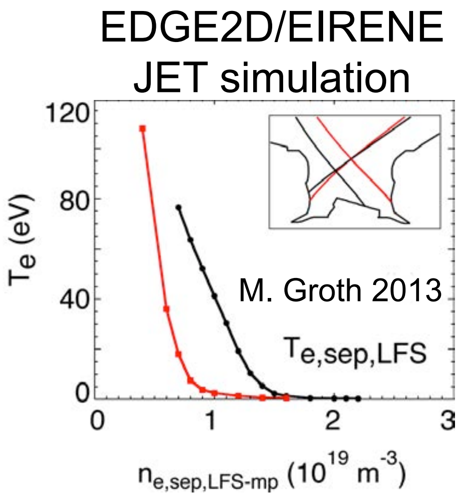
High-Z Erosion Rates Measured in DIII-D



1. **Material science laboratories:** Design and evaluate new candidate materials
2. **Linear facilities:** Expose candidate materials to relevant test environments
3. **Tokamaks:** Evaluate samples under plasma exposure (short & long pulse)

Pulse length requirements are driven by sensitivity of the measurement.

Enhanced Simulation Efforts Are Needed to Develop Validated Predictive Capability to Guide PFC Design

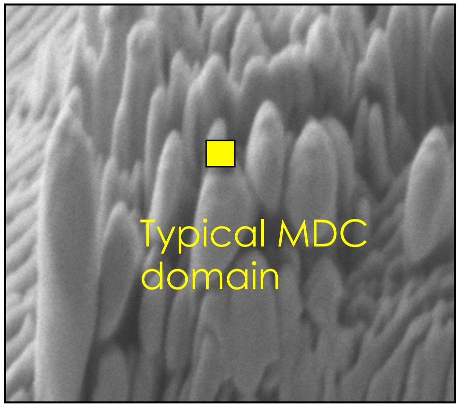


- **Validated Simulations are key to quantitative divertor optimization *and* to <u>Materials</u> design/development**
  - Processes are coupled, nonlinear, multi-dimensional
  - Quantitative prediction beyond the reach of analytical models

- Present effort on Boundary/SOL/Divertor/PMI simulation is subcritical given the demand and challenge

- Close interaction with experiment is needed (analysts)

- Startup: 2 centers: 1 plasma + 1 materials (***BES partners***)



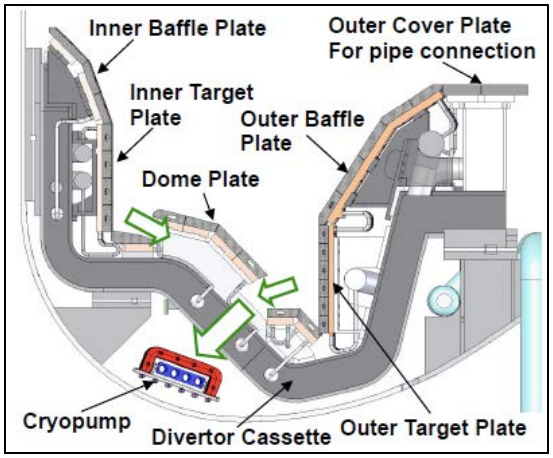
Bndry Plasma Solutions   Develop Materials

Self-Consistent Core – Edge Solutions Must Be Evident to Begin FNSF Design

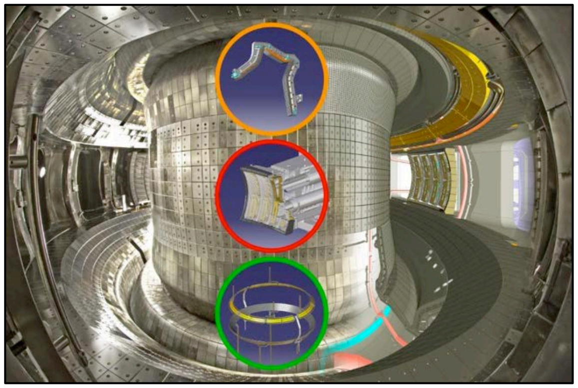
- **Upgrades to US tokamaks offer a cost effective start on core-edge integration**
  - Develop non-inductive scenarios (startup, ramp-up, high Te/Ti, low rotation)
  - Explore integrated divertor operation: new components, materials, high temp walls
  - Develop disruption avoidance and mitigation systems

- **Enhanced collaborations with SC tokamaks provide sufficient pulse length for materials to reach steady-state conditions**
  - High performance stability and control for many resistive times: $2\tau_R \rightarrow 50\tau_R$
  - High-heat flux components in thermal equilbrium (recycling, etc.)
  - Explore/confirm long term trends in material migration

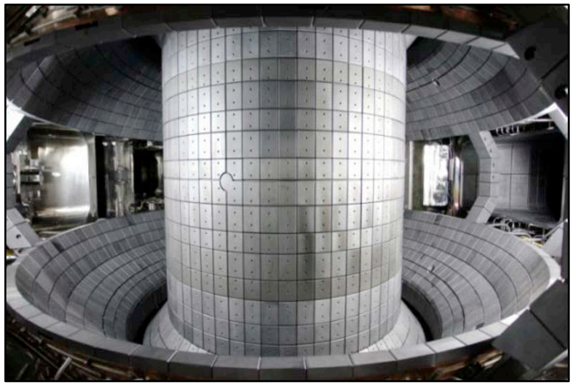
JT-60SA (2019): 100sec



EAST: 1000sec



KSTAR: 300sec



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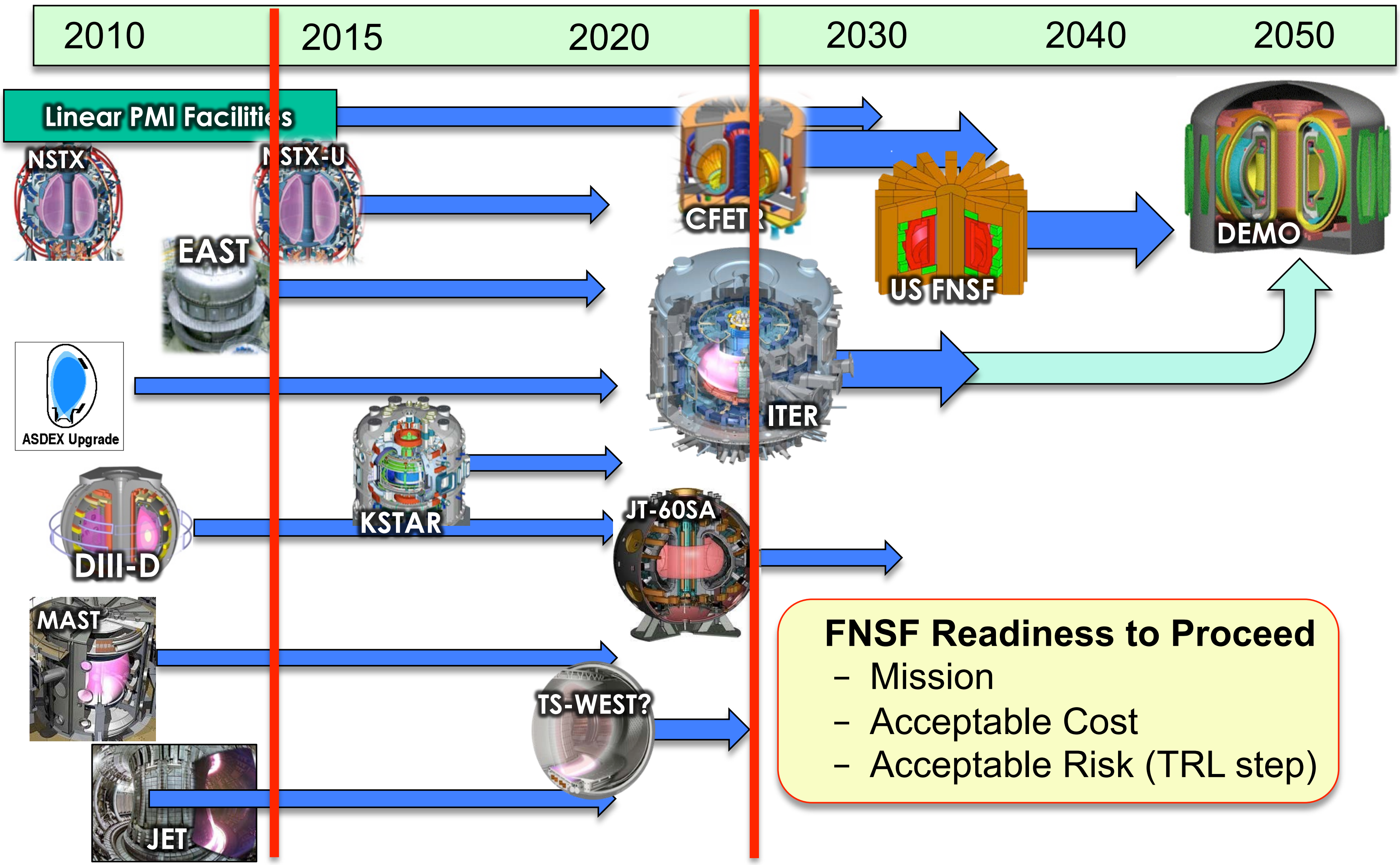
Consistent with ReNeW Theme 3: Taming the Plasma Material Interface

additional backup material

Time Is Short to Address the PMI Challenge For Being Ready to Start FNSF Design In 2025



Realistic Assessment of Scientific Goals, Cost, & Schedule Must Drive Investments in DivSOL – PMI Research

- **What is required to advance Technical Readiness Levels?**
- **Where best to do the work? (required research capabilities)**
- **When will required new capabilities be available and at what cost?**

Eight specific investment options	**New Facility Operating Cost (ea.)**
✔ 1. Theory/Computational Research Groups	($6 – 20M/yr)
✔ 2. Linear PMI and SOL physics facilities	($25M facility/ $5M/yr)
✔ 3. Existing non-activated tokamaks	($50M upgrades/$30M/yr)
4. Other new long-pulse, non-activated tokamaks	($300M /$50M/yr)
✔ 5. Very long-pulse, high performance tokamaks	($1B /$100M/yr)
6. ITER	($30B /$1500M/yr)

Specific Challenges of DEMO-scale Fusion Related to the Plasma Boundary (Plain English Version)

Closely linked by plasma physics

- **Fueling and density control, ash removal**
- **PFC melting due to steady and transient heat loads**
- **Impurity control**
- **PMI: sputtering, erosion, and changes to surface structure/composition**
- **Structural damage due to neutrons and helium implantation**

Strongly linked by material choices

Failure Consequence: No Fusion (first three items); Short Lifetime (PMI and structural damage)

Three Initiatives to Address These Challenges:

Plasma-Based Solutions, PFC/Materials Development, Core/Edge Integration