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New Directions in the Fusion Energy Program at LLNL

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Fusion Power Associates
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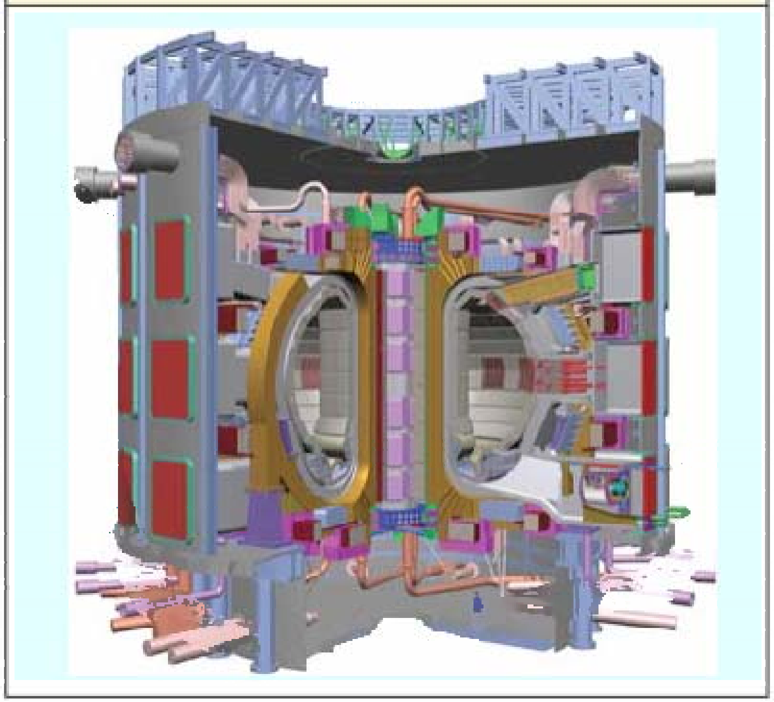
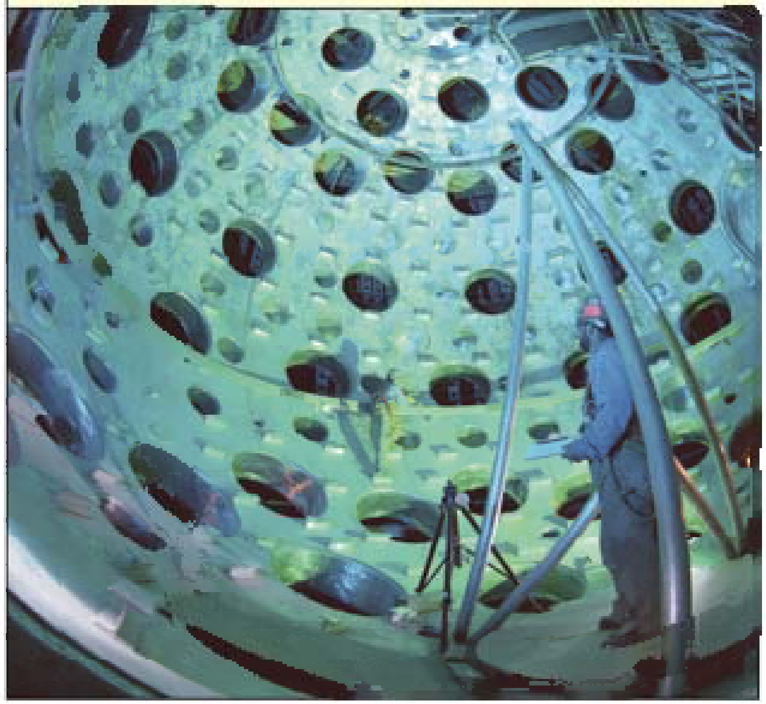
We are entering the era of laboratory burning plasmas – Two experiments define what LLNL will pursue

Magnetic Fusion Energy



DOE Office of Science

Inertial Fusion Energy



DOE NNSA

Each will answer physics questions critical to fusion energy's success. But we need to ask:

Q: On the path through ITER to DEMO, what are the gaps in MFE that provide opportunities?

Q: Building on NIF ignition, what science will go farthest in making IFE attractive?

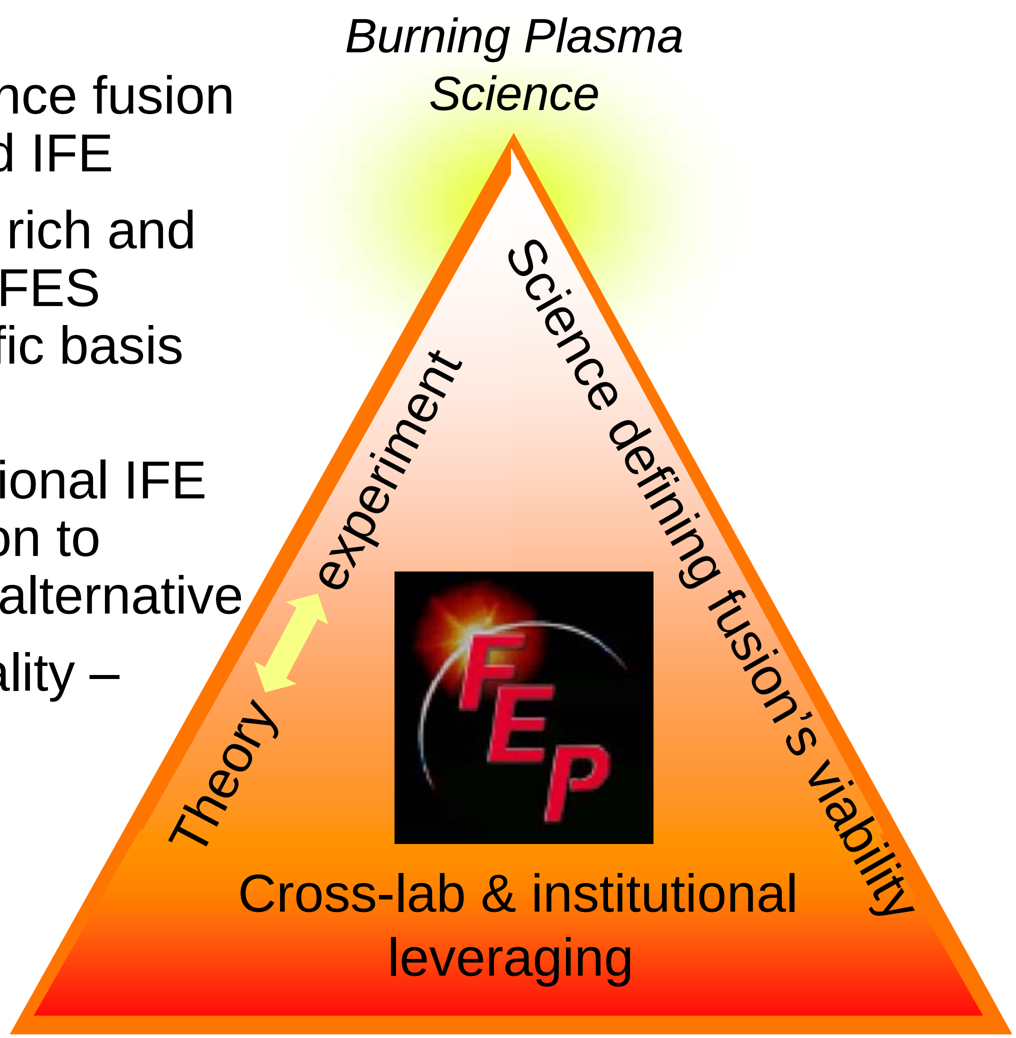
Q: How can lab capabilities be leveraged to maximize science output to advance MFE & IFE?

The FEP focuses on problems that can alter the vision of what an energy producing system will look like

- MFE
  - Addressing key questions for ITER and DEMO that are rich in multiscale physics
  - Engaging in burning plasma control science through ITER diagnostics
  - Leveraging broader lab capabilities in materials science and computation
  - Reaching for a leadership role in the National Fusion Simulation Project (FSP)
- IFE
  - Developing the ability to study burning plasma science in the laboratory via active engagement in the NIF ignition program
  - Developing the scientific basis for fast ignition via strong participation in an integrated effort involving LLNL scientists and external collaborators
  - Examining target design, target chamber, and other issues as part of the broader LLNL LIFE strategy
  - Pursuing advances in heavy ion fusion: New promise is stimulated by direct drive simulations and a new design for NDCX-II

LLNL FEP seeks to advance the science related to fusion's high leverage, pressing multi-scale science challenges

- Transformative science will enhance fusion energy's viability in both MFE and IFE
- These problems are scientifically rich and speak to Office of Science and OFES mandates to establish the scientific basis for fusion energy
- We are an integral part of the national IFE strategy and the laboratory's vision to develop LIFE as a fusion energy alternative
- Community connections yield vitality – collaboration, cross-discipline, and intra-lab



Magnetic fusion energy science

On the path to DEMO, ITER addresses many of the challenges, but there are important gaps

ITER - First operations in ~2018

What are the next steps, new facilities on the path to demo

?

- Greenwald Panel report to FESAC "Priorities, Gaps and Opportunities" identified R&D gaps and possible new initiatives to address them

How Initiatives Could Address Gaps

Legend

Major Contribution	3
Significant Contribution	2
Minor Contribution	1
No Important Contribution	

	G-1 Plasma Predictive capability	G-2 Integrated plasma demonstration	G-3 Nuclear-capable Diagnostics	G-4 Control near limits with minimal power	G-5 Avoidance of Large-scale Off-normal events in tokamaks	G-6 Developments for concepts free of off-normal plasma events	G-7 Reactor capable RF launching structures	G-8 High-Performance Magnets	G-9 Plasma Wall Interactions	G-10 Plasma Facing Components	G-11 Fuel cycle	G-12 Heat removal	G-13 Low activation materials	G-14 Safety	G-15 Maintainability
I-1. Predictive plasma modeling and validation initiative	3	2		2	2	3	1		2						
I-2. ITER – AT extensions	3	3	3	3	3		2		2	2	1	1		1	1
I-3. Integrated advanced physics demonstration (DT)	3	3	3	3	3	1	3	2	3	3	1	1	1	1	1
I-4. Integrated PWI/PFC experiment (DD)	2	1		1	2		2	1	3	3	1	1		1	1
I-5. Disruption-free experiments	2	1		2	1	3		1	1	1					
I-6. Engineering and materials science modeling and experimental validation initiative							1	3	1	3	2	3	3	2	1
I-7. Materials qualification facility							1			3	2	1	3	3	
I-8. Component development and testing			1				2	1		3	3	3	2	2	2
I-9. Component qualification facility	1	1	2	1	2		3	2	2	3	3	3	3	3	3

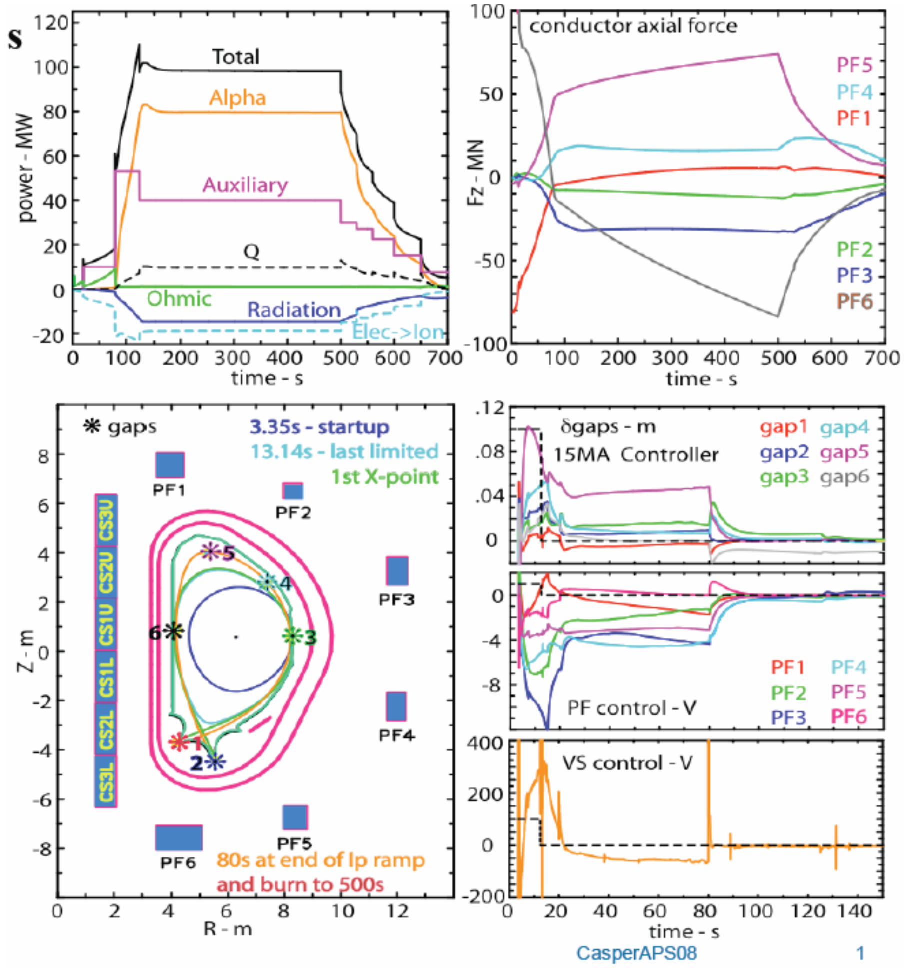
The LLNL FEP can play a major role in addressing the Greenwald Panel gaps

- FEP currently has (or is positioning itself for) leadership capability in a major facet of
  - Plasma predictive capability (G1)
  - Nuclear capable diagnostics (G3)
  - Control near limits (G4)
  - Fuel cycle (G11)
  - Heat removal (G12)

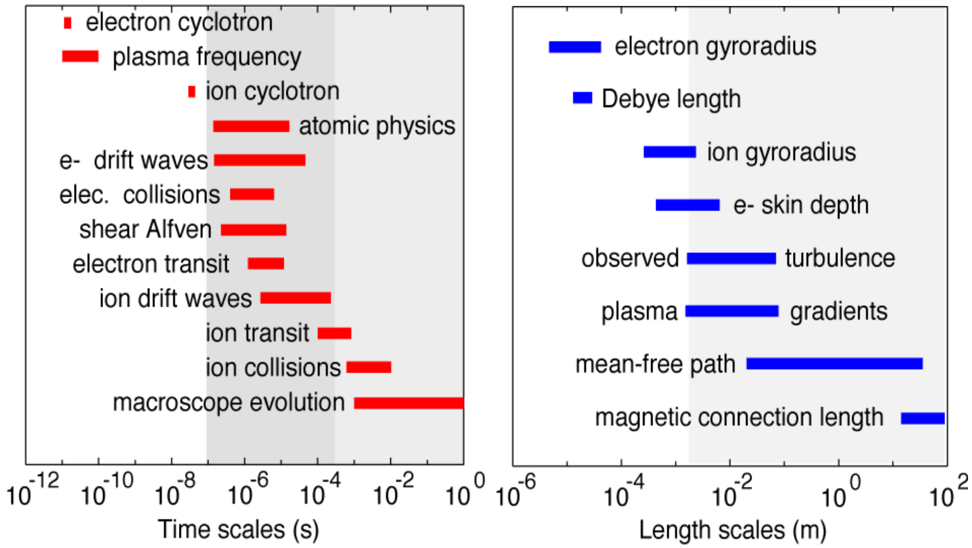
- FEP could assert leadership with Laboratory leverage
  - Plasma wall interaction (G9)
  - Plasma facing components (G10)
  - Low activation materials (G13)

Our plasma control expertise has been of high value in answering ITER design review questions

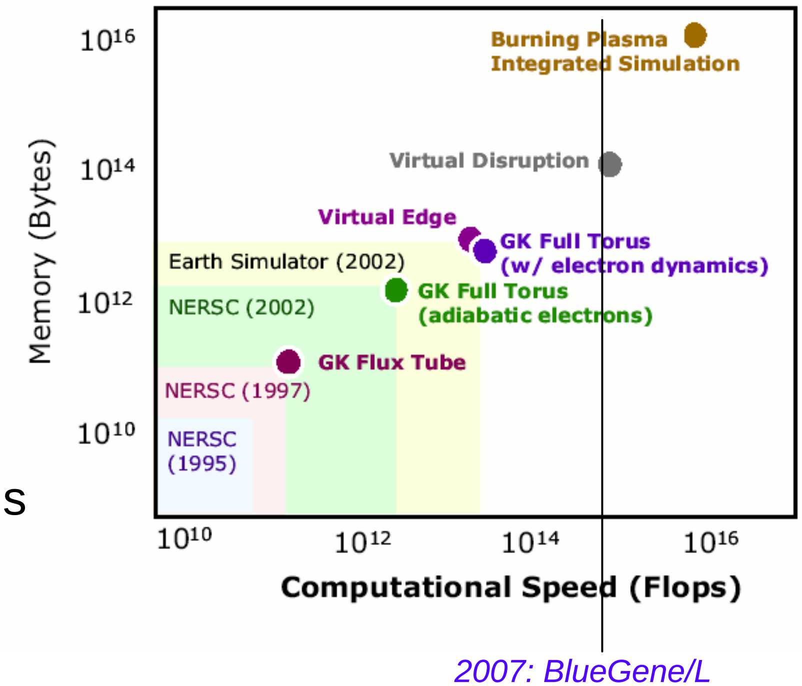
- Clarified requirements for PF coil system and plasma startup
- The ITER Office asks for this work to help resolve urgent questions (e.g., vertical stability)
- A continuing challenge is generating systematic support out of OFES



Grand challenge for fusion: simulate a burning plasma with a validated model that captures the relevant multiscale physics



From first FSP report (Dahlburg)



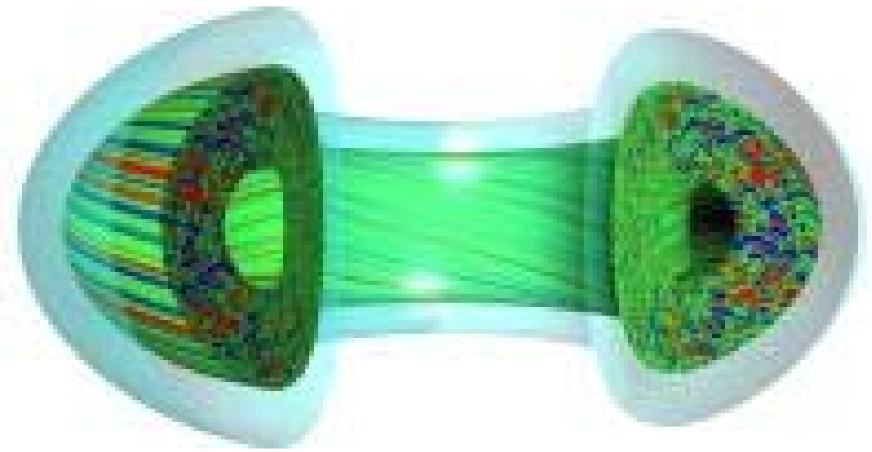
- The Fusion Simulation Project: A tremendous multi-scale physics challenge. OFES envisions a ~ 20 year, $25 M/yr effort
- Ambition/need for full device simulation may include *exascale* computing (10^{18} flops)
- One aim of FSP: impact on how ITER research is planned at the end of the next decade

Gap 1: Predictive Capability

To be a major player in the FSP, the FEP will build on existing activities and leverage capabilities elsewhere in the lab

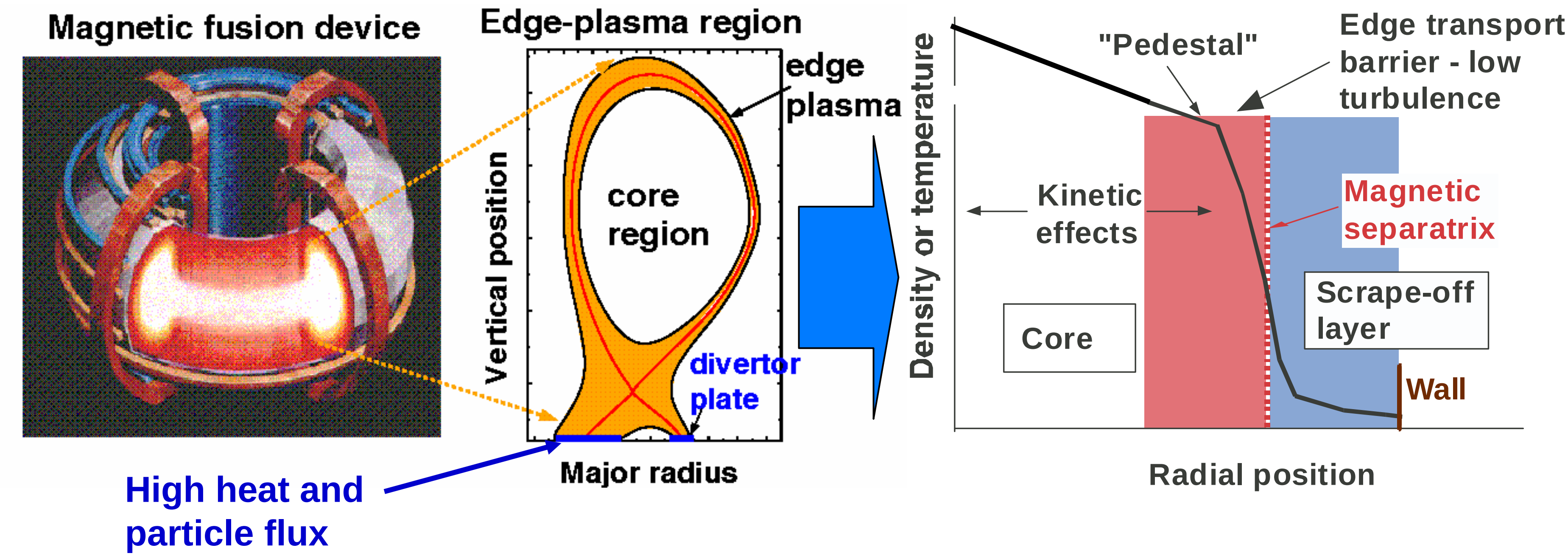
- **Elements in place include**
  - Edge Simulation Laboratory (leverages TEMPEST Strategic Initiative)
  - SciDAC: co-PI's on FACETs - a "proto FSP"
  - SciDAC: PI, core turbulence codes development (collaboration w/ PPPL, MIT, GA, U. of Colorado)
  - LLNL LDRDs - Core turbulent transport data analysis, Advanced divertor theory and simulation, and Edge modeling and simulation

- **Further leveraging within LLNL could include**
  - V&V expertise from ASC would be first-of-kind if plied in MFE
  - Massively parallel computing - offering BG/L, Thunder, Atlas & descendants as a national resource
  - Expertise in integration of codes



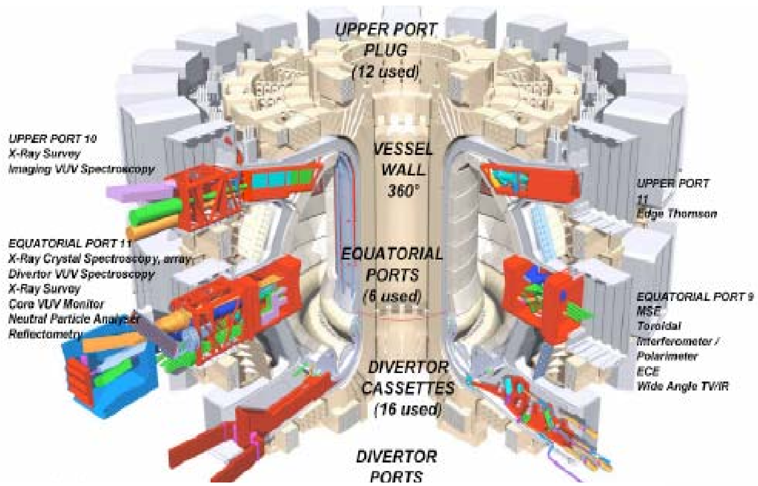
From GYRO code (GA) - performance scales well on BG/L (32,000 processors run thus far)

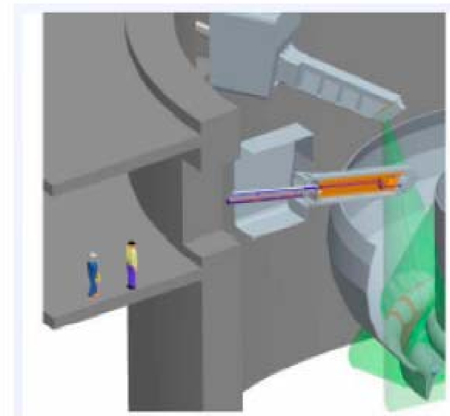
Many of the Gaps and Opportunities have boundary physics and control as major components



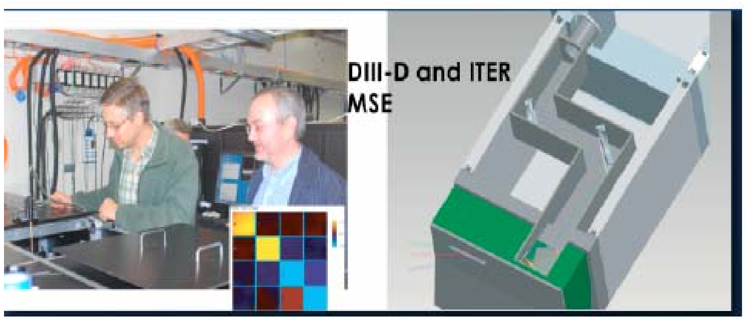
- Demands of DEMO: manage the radiant heat flux at the surface of the Sun; or a re-entering Space Shuttle in steady-state.
- Understanding is a multiscale, multidiscipline challenge: varying length scales, physics of sources & sinks, transport on closed vs. open field lines.
- Heat and particle impulses dominate in H mode. Concern for ITER, DEMO: wall melting.
- ITER-relevant, scrape-off layer and divertor physics conducted by FEP at DIII-D.

FEP is developing diagnostics for plasma control on ITER





- **Real-time heat flux measurements** essential to protect ITER



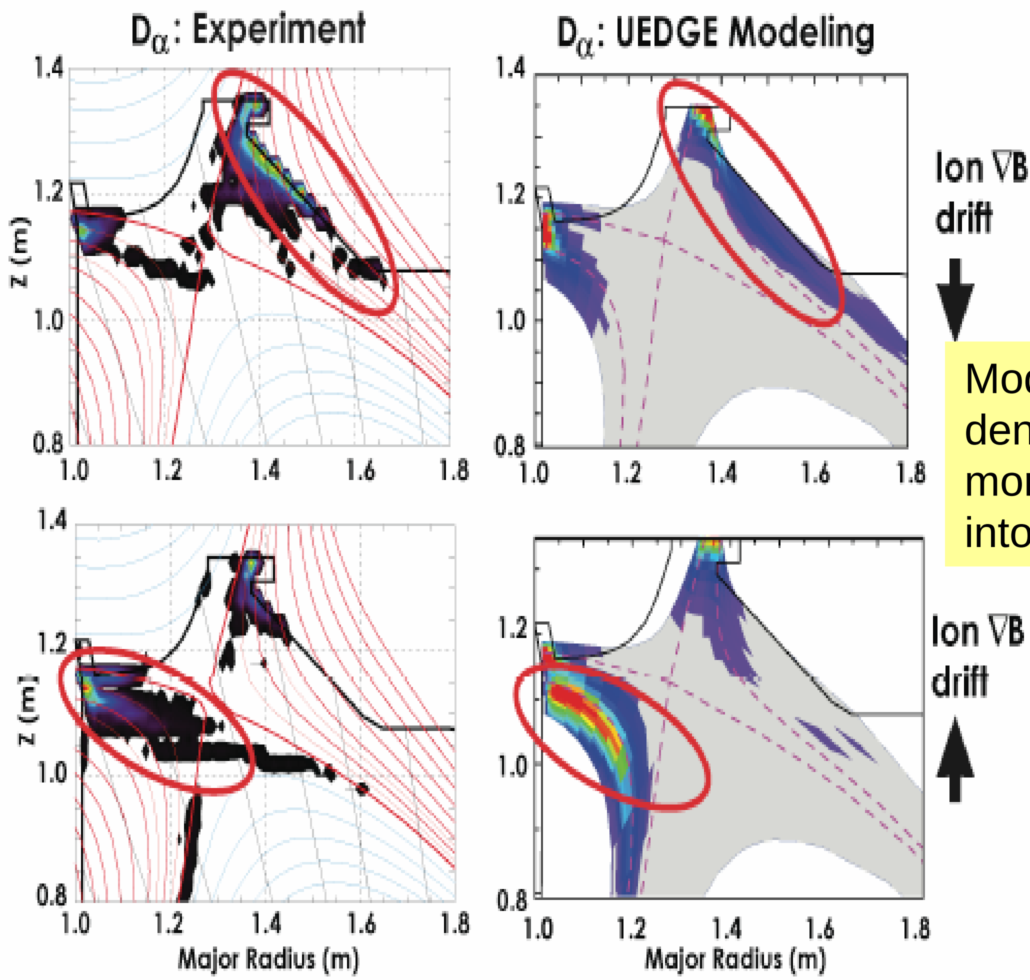
- **Current density profile measurements** essential for burning plasma control

EBIT

- **x-ray crystal spectroscopy for Ti and rotation** planned for ITER

Our DIII-D work is characterized by strong coupling of experiment and modeling

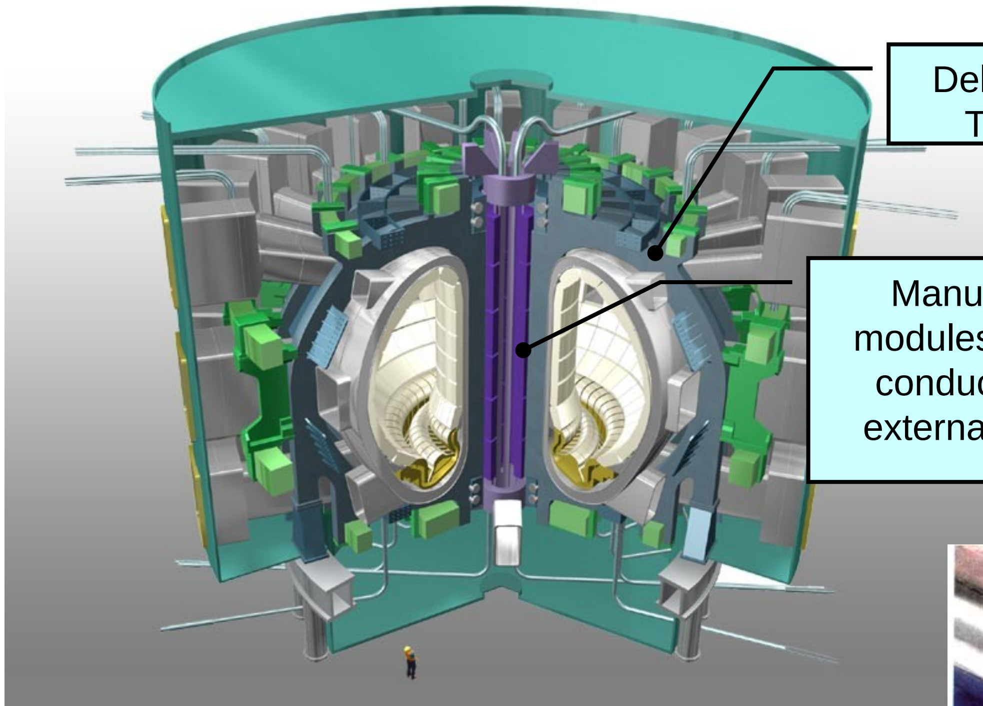
- ion B×∇B↓: recycling dominant in outer divertor
- ion B×∇B↑: recycling dominant at inner divertor target



Modeling suggests better density control enabled by more favorable ExB drifts into outer pump

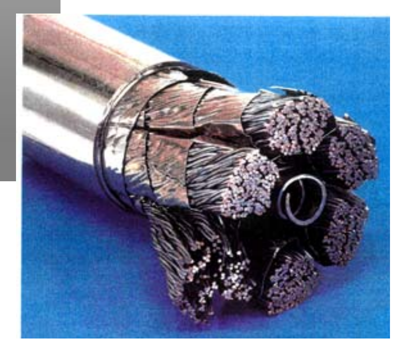
FEP research is a major contributor to ITER magnet design and qualification work

ITER Magnet Systems (US share)



R&D items

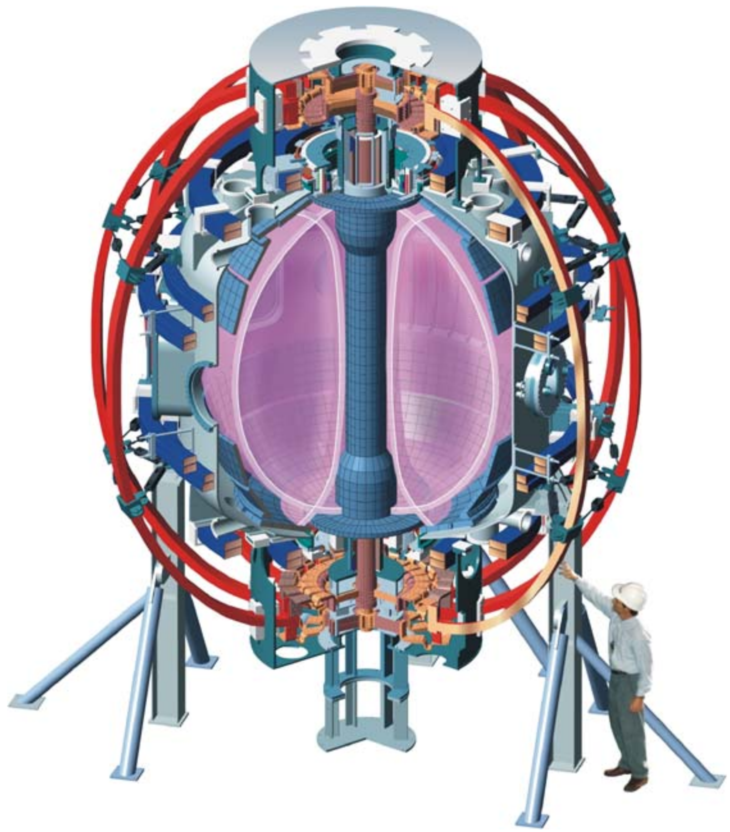
- Butt joint development
- TF conductor qualification
- Turn insulation qualification



Nearly 40 t of Nb_3Sn wire

OFES's recent commitment to NSTX creates an opportunity to leverage our boundary physics strengths

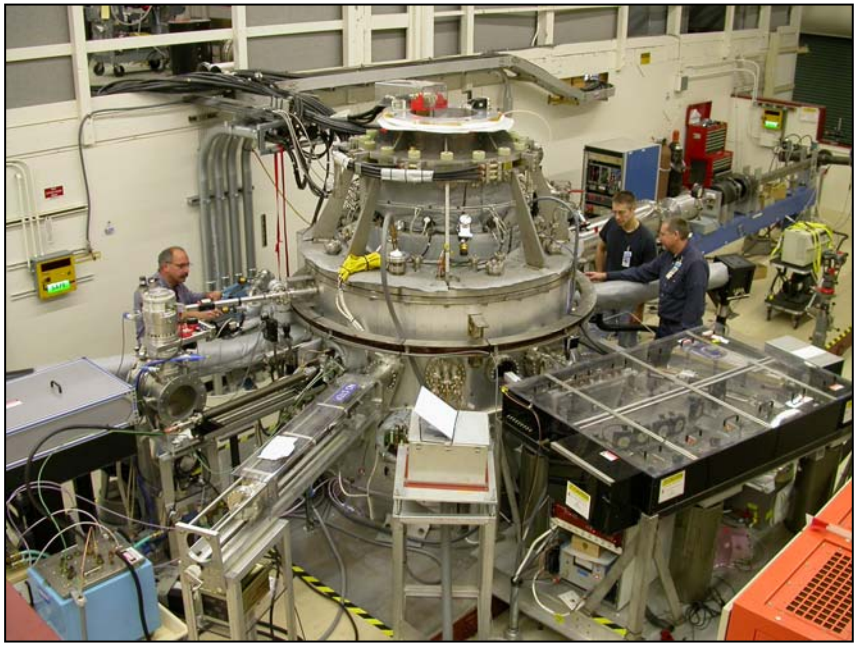
- NSTX has sharpened focus: CTF relevance, including managing the enormous heat fluxes at the boundary
- We are developing a proposal to strengthen our role at PPPL, in collaboration with their team members.
- Working to couple this with increased LDRD investment targeting DIII-D research.



NSTX, PPPL

In consultation with OFES, we ended the SSPX spheromak program and redirected resources to short-pulse HEDLP

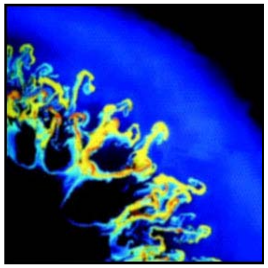
- The SSPX team set the ICC community’s highest standards in V&V simulation and theory of resistive MHD.
- After a review, OFES agreed that it is reasonable to pause spheromak research nationally at this scale, and that it is in their strategic interest to redirect this support to HEDLP.



The SSPX Team and leadership is to be applauded for its record of scientific achievement and praised for its excellent safety record.

FEP continues to make key contributions to laser-driven IFE

- New short-pulse HEDP program to experimentally validate modeling of fast ignition physics

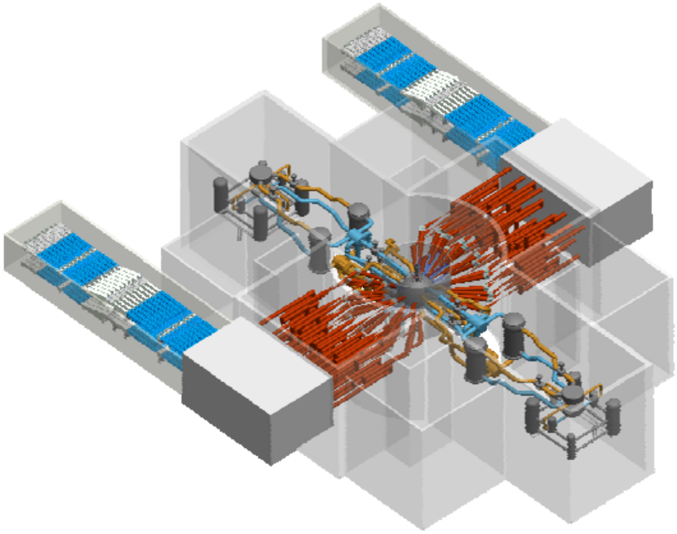


3D Rad-Hydro

TITAN Laser

- Contributions to the LIFE project in the areas of fast ignition targets, chambers, and driver/chamber interface

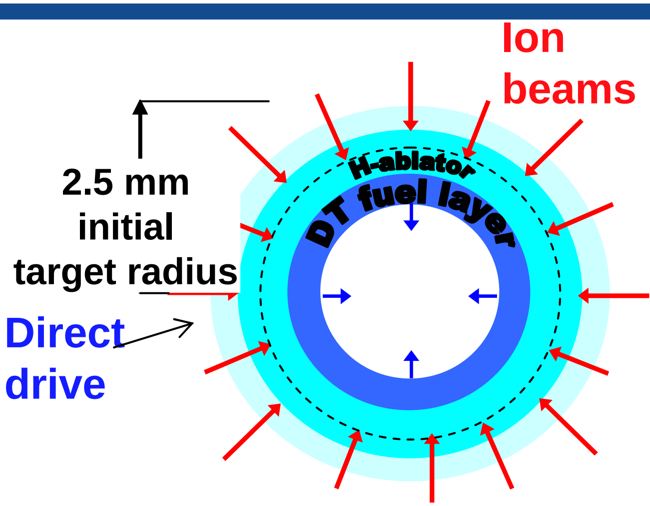
These topics were covered in the IFE talk by Ed Moses

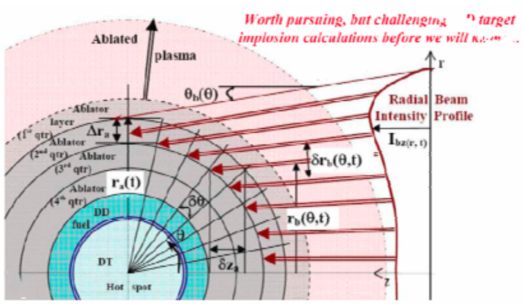


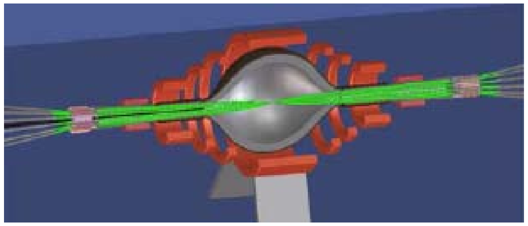
LIFE Power Plant

Heavy ion fusion science will benefit from NIF ignition, and recent studies reveal new promise

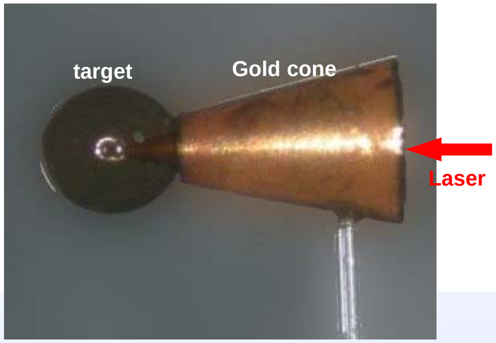
- Highly collaborative: the Virtual National Laboratory for Heavy Ion Fusion Science - LBNL, LLNL, PPPL.
- NIF will provide target physics validation relevant to HIF
- Ion direct drive potentially game-changing for IFE - promise of increasing efficiency to 25% by ramping driver energy to penetrate outgoing ablator. ==> reduction in driver energy from 7 MJ to 1 MJ
- New particle mover for HIF benefits fast ignition: Enables faster simulation of particle motion with large grad-**B**. Alternative to MFE gyrokinetics?

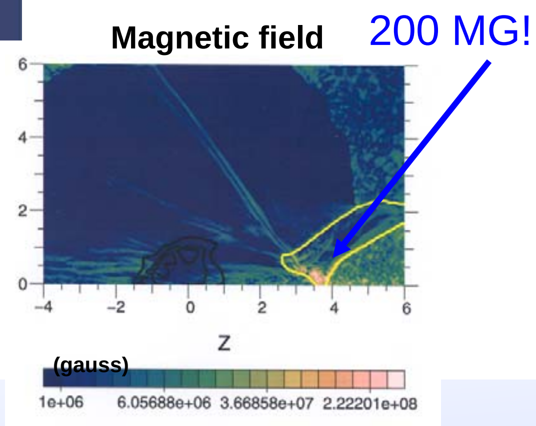




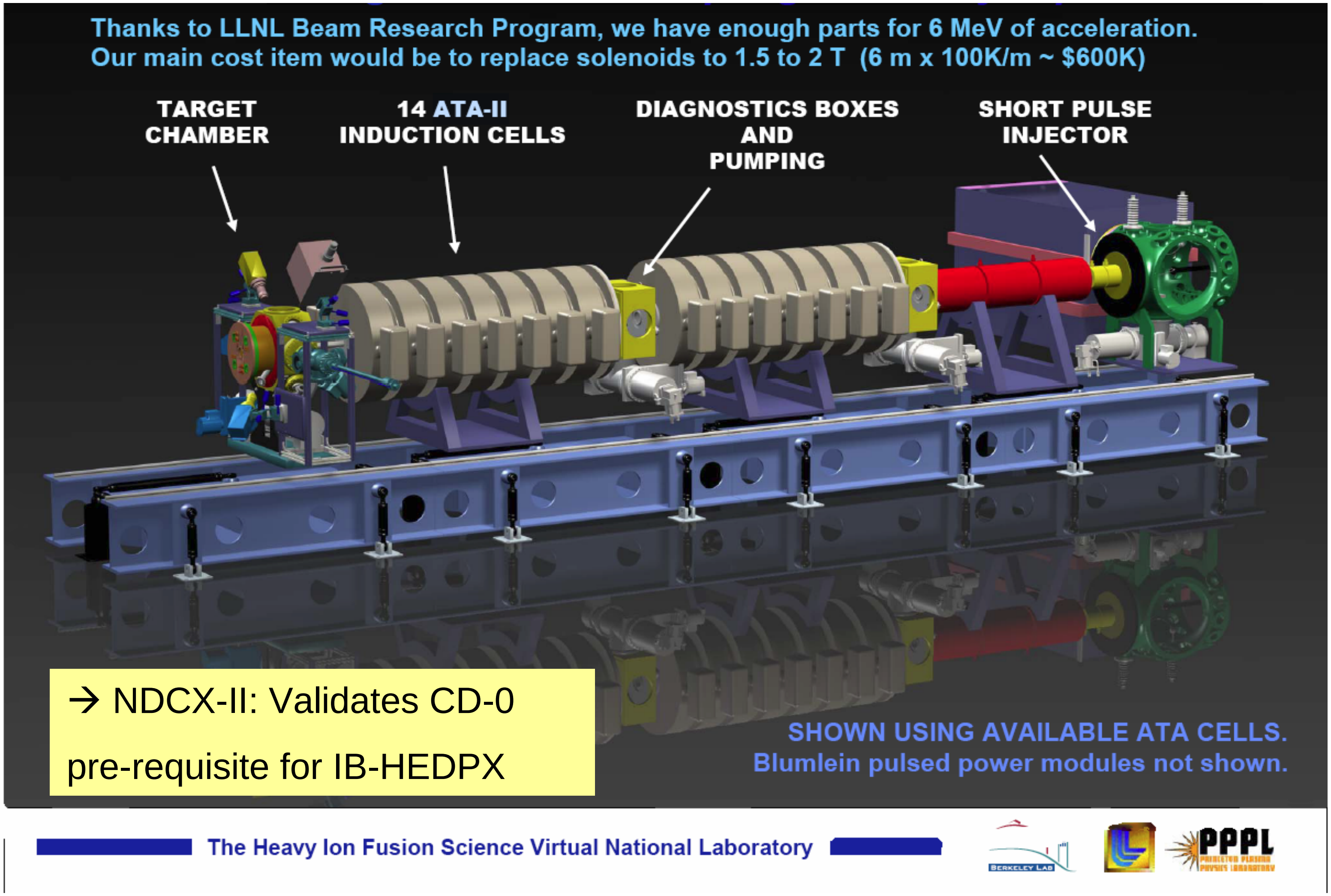


Polar direct drive analysis is promising as well ==>> two-sided illumination





The HIFS-VNL group has identified a route to a next-step device that would advance IFE science



The science we pursue can have a significant impact on key issues related to practical fusion energy

- We are entering the era of burning plasmas. In this era, the FEP will take on problems that may impact fusion energy system’s fundamental architecture and viability.

- Success in the burning plasma era will require the FEP to strengthen existing partnerships and create new ones, leveraging capabilities both inside and outside of this laboratory.

- NIF and LIFE are providing exciting new opportunities for FEP at LLNL

Fusion Energy Program

Physical and Life Sciences Directorate
Lawrence Livermore National Laboratory