The U.S. fusion energy science program, LLNL's effort, and opportunities for constructive partnership

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U.S. - Japan Workshop on Heavy Ion Fusion and High Energy Density Physics

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The science we pursue can have a huge impact on the well-being of future generations, but we have to work together even more effectively to make a difference

- In the emergent burning plasma era, the nation and the world must take on problems that will determine a fusion energy system's fundamental architecture and viability. **Heavy ion fusion is part of this dialogue**

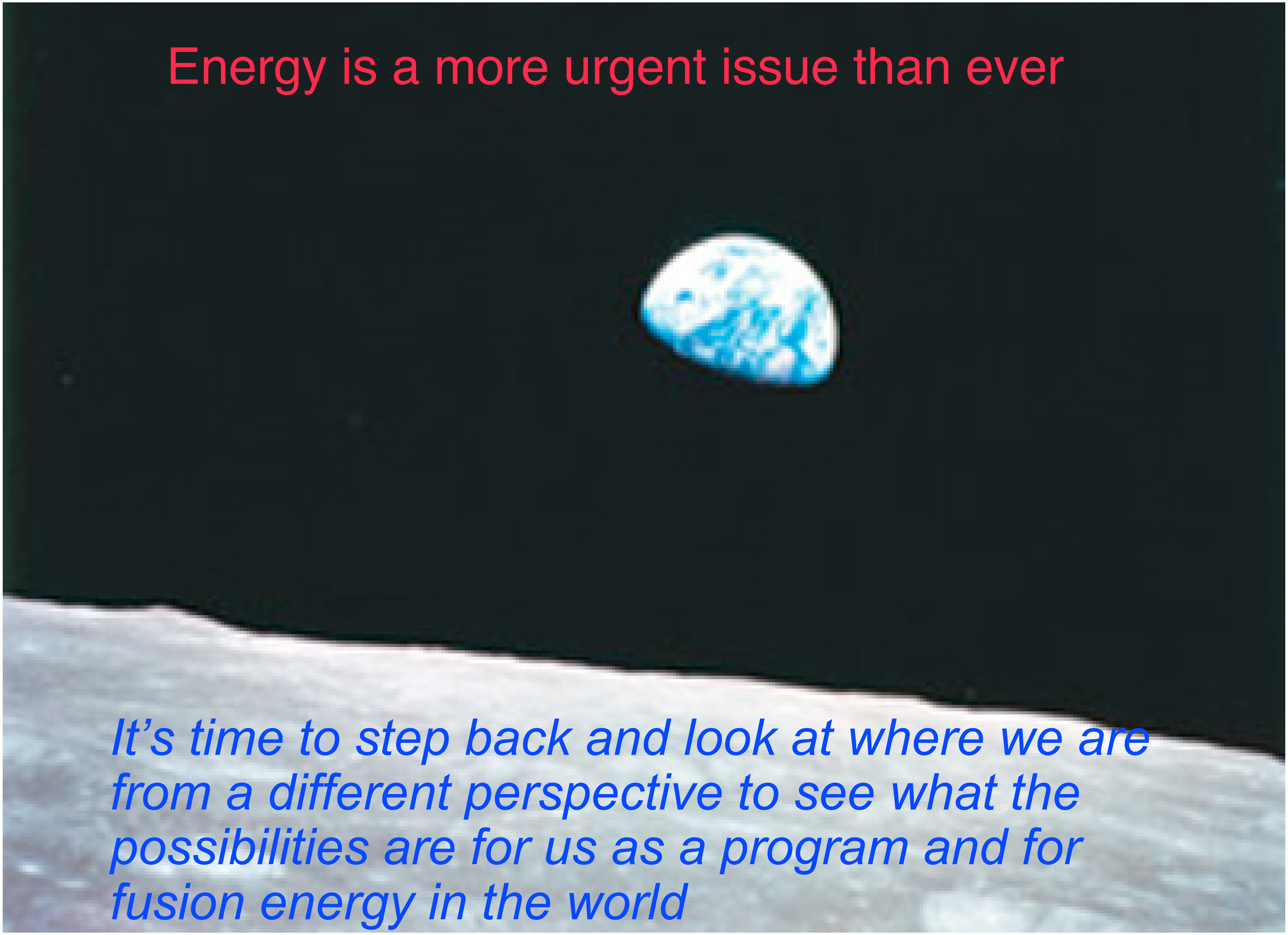
- But overall, **there is a credibility gap**. The present level of effort won't get us to where we need to be to become credible

- **What we can do** towards this is promoting a new level of constructive engagement. There is lots of opportunity; plenty of common interests, including between MFE and IFE

Emphasized here:

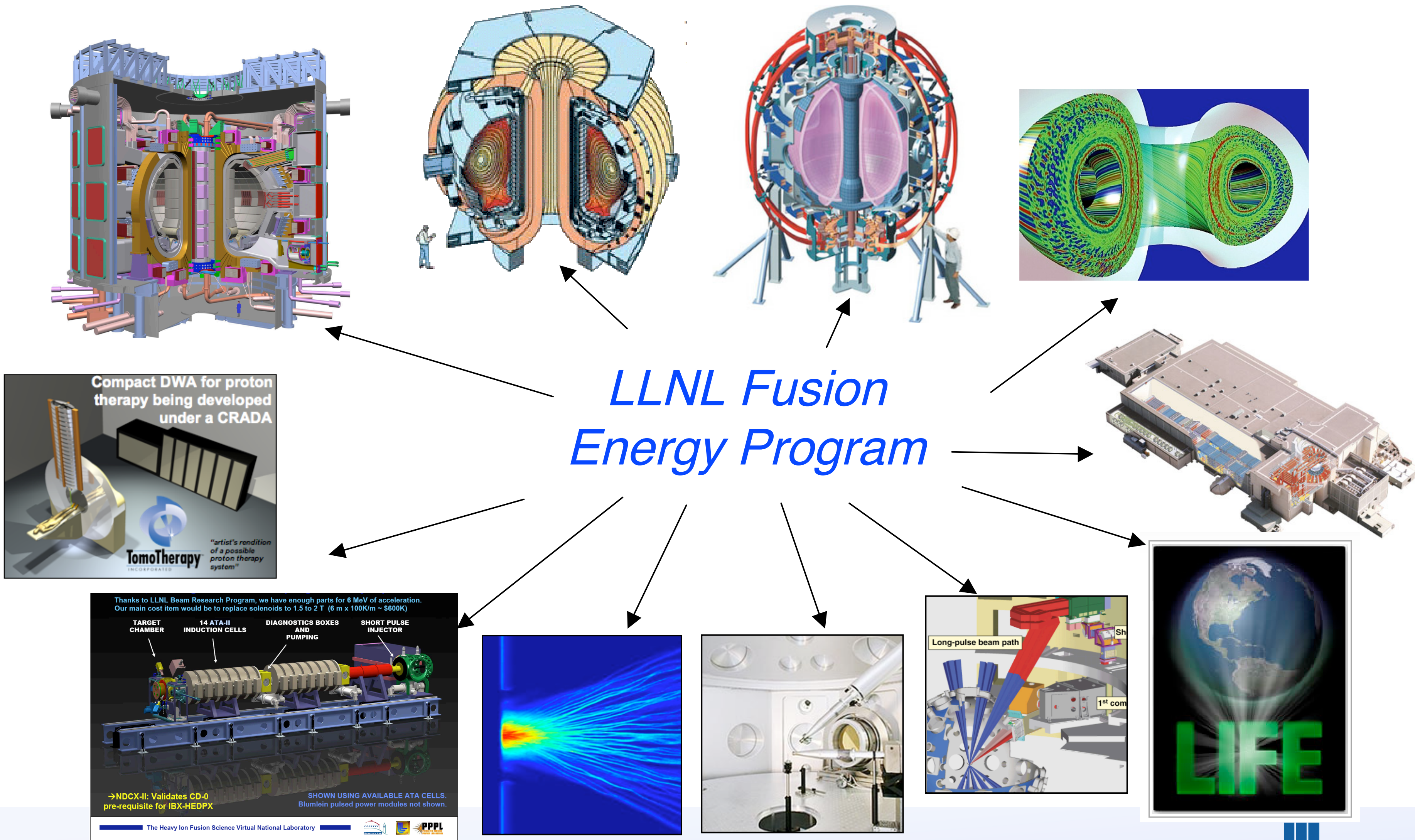
- *Background on the the LLNL Fusion Energy Program, especially in the context of U.S. OFES research directions. Emphasis on where we see partnering opportunities*
- *Looking for synergy between IFE and MFE science*
- *Requirements and challenges for HIF to move forward in the era following NIF ignition*

Energy is a more urgent issue than ever



It's time to step back and look at where we are from a different perspective to see what the possibilities are for us as a program and for fusion energy in the world

The LLNL Fusion Energy Program is broad. The challenge and opportunity is in identifying and building on the interconnections



The science we pursue can have a huge impact on the well-being of future generations

What I tell our own LLNL FEP program:

- In the burning plasma era, we need to take on problems that may well determine a fusion energy system's fundamental architecture and viability.

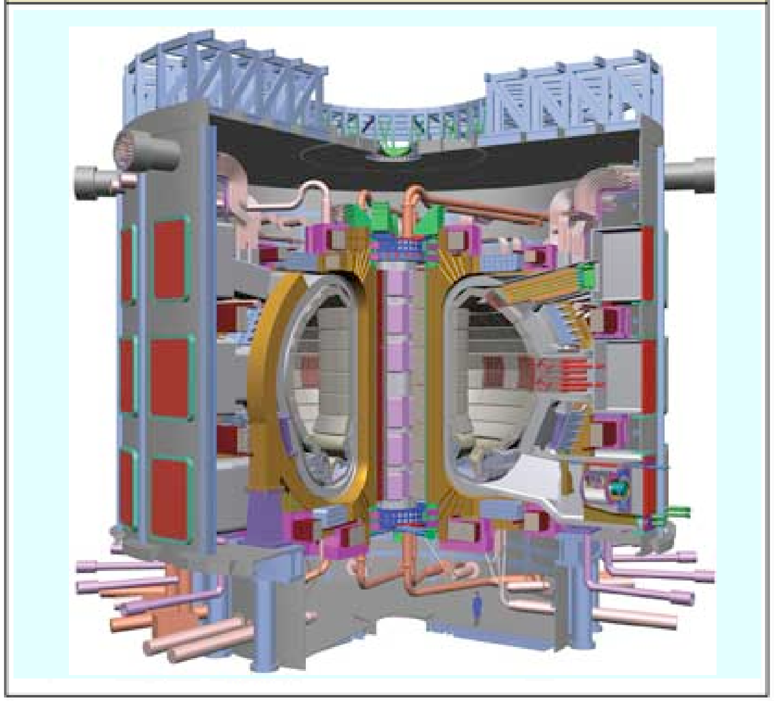
Heavy ion fusion certainly is this kind of challenge

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

Leveraging and partnering is a hallmark of HIF work, but it needs to look hard for opportunities outside of its community

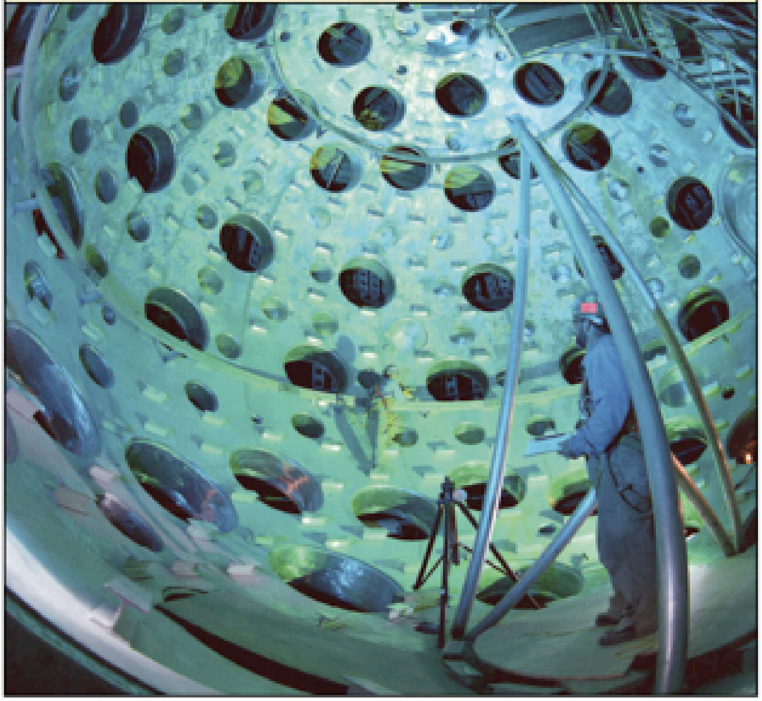
There are two emergent burning plasma experiments that define what LLNL pursues

Magnetic Fusion Energy



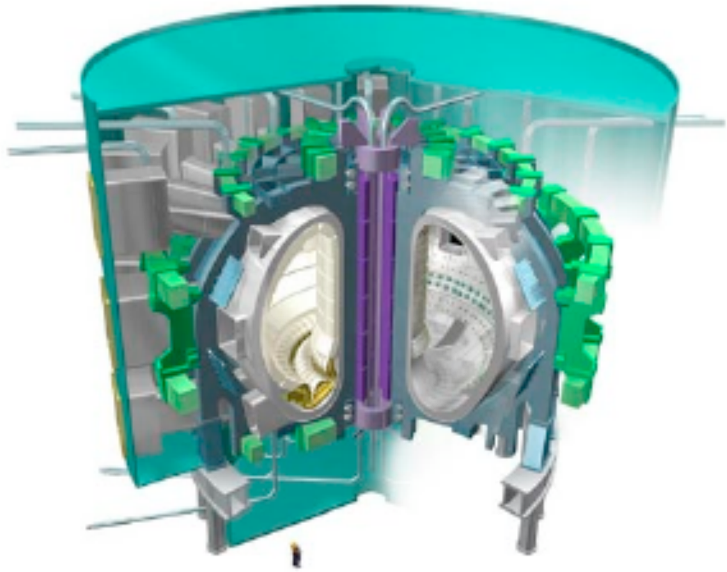
DOE Office of Science

Inertial Fusion Energy



DOE NNSA

Consider MFE: on the path to DEMO, ITER defines many of the challenges, but there are important gaps



ITER - First operations in ~2019
Site prep underway

M.U.S.E. - "Major U.S. Experiment" - to be defined

?

- Orbach question: "What will make this statement true: 'ITER is the penultimate step to DEMO'?"
- U.S. answers in Greenwald Panel "Gaps and Opportunities Analysis" summary, next slide==>>

Many of the gaps identified in MFE research worldwide are relvant to IFE

From Greenwald Panel's "Gaps and Opportunities" Report

MFE/IFE Joint opportunities?

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

Present FEP leadership capacity in a major facet of this topic

G4 - Control near limits
G11 - Fuel Cycle
G12 - Heat Removal

FEP positioning itself to compete or participate in new U.S. efforts

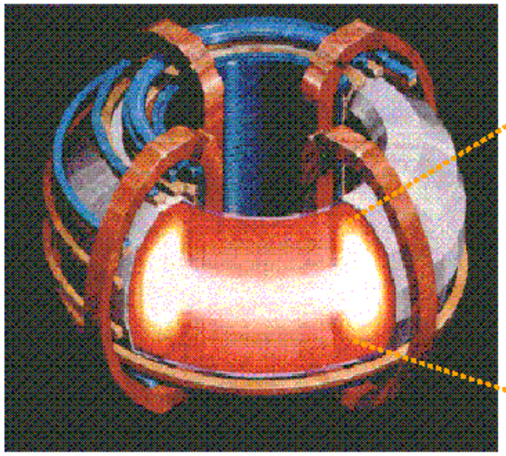
G1 - Plasma Predictive Capability
G3 - Nuclear capable diagnostics

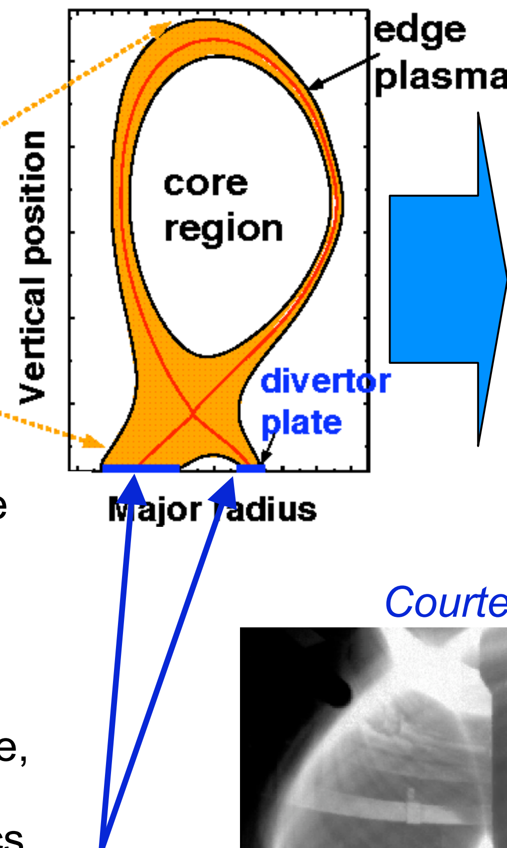
LLNL-FEP could assert leadership w/ lab leverage

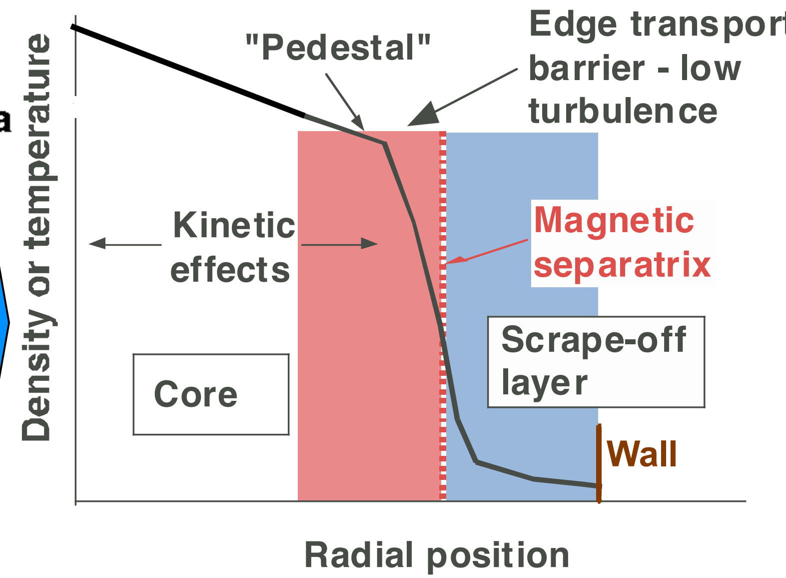
G9 Plasma Wall Interactions
G10 Plasma Facing Components
G13 Low activation materials

Many of the MFE Gaps and Opportunities have boundary physics as major components, a LLNL strength.

Magnetic fusion device



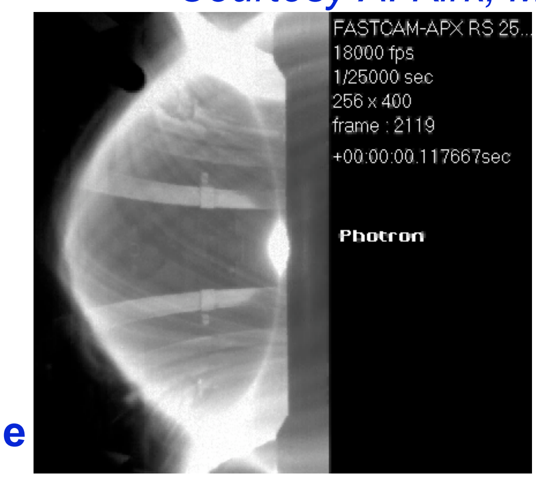




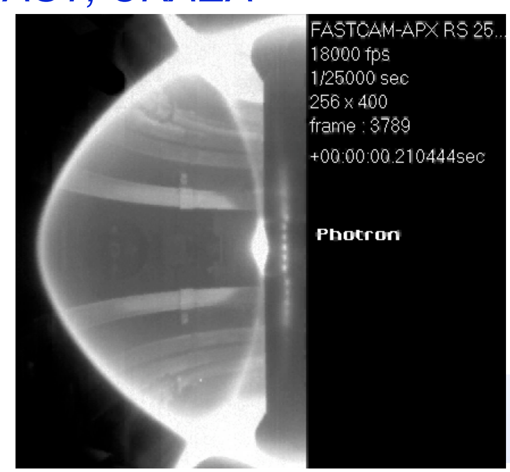
- Demands of DEMO: manage *the radiant heat flux at the surface of the Sun*; or a *re-entering Space Shuttle in steady-state*.
- Understanding is a multiscale, multidiscipline challenge: varying length scales, physics of sources & sinks, transport on closed vs. open field lines … a grand challenge like IFE/ICF integrated modeling

High heat and particle flux

Courtesy A. Kirk, MAST, UKAEA



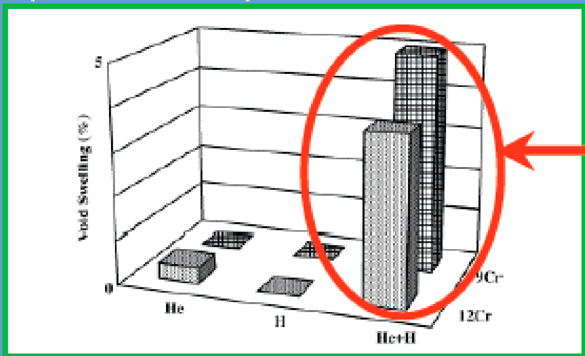
L mode: turbulence



H mode: big heat bursts

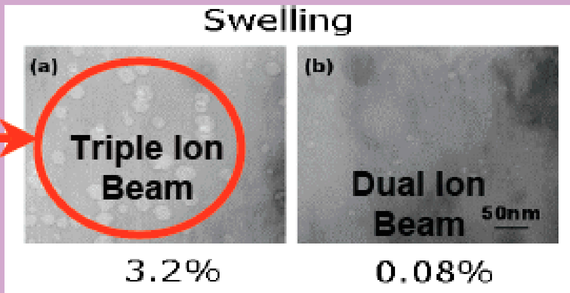
MFE and IFE can promote developing a common approach to materials science issues by leveraging existing facilities

The synergistic effect of He and H was shown clearly in the triple ion (Fe^{3+} + He^{+} + H^{+}) irradiation



T. Tanaka et al. JNM 329-333(2004)294

The average swelling in F82H steel was significantly enhanced by the triple ion irradiation.



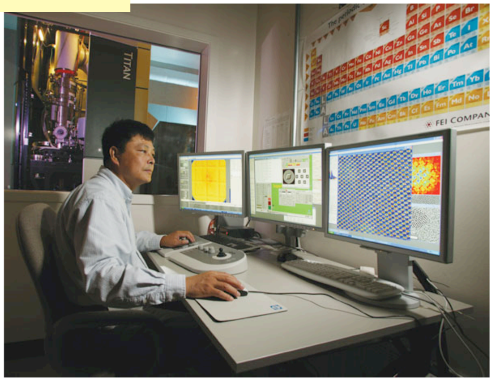
E. Wakai, et al. JNM 307-311(2002)278

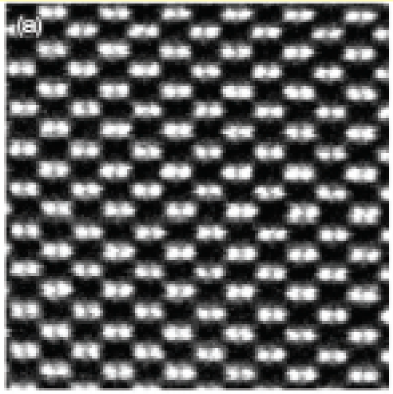
CAMS and a possible triple ion beam facility may explore synergistic 3 ion effects: relevant for fusion wall materials?

SuperSTEM can look at materials at the atomic level

"Greenwald Gaps": Plasma-surface interactions, plasma facing components, heat removal, fuel cycle

LLNL capabilities may be applicable to emergent OFES emphasis on the plasma/materials interface





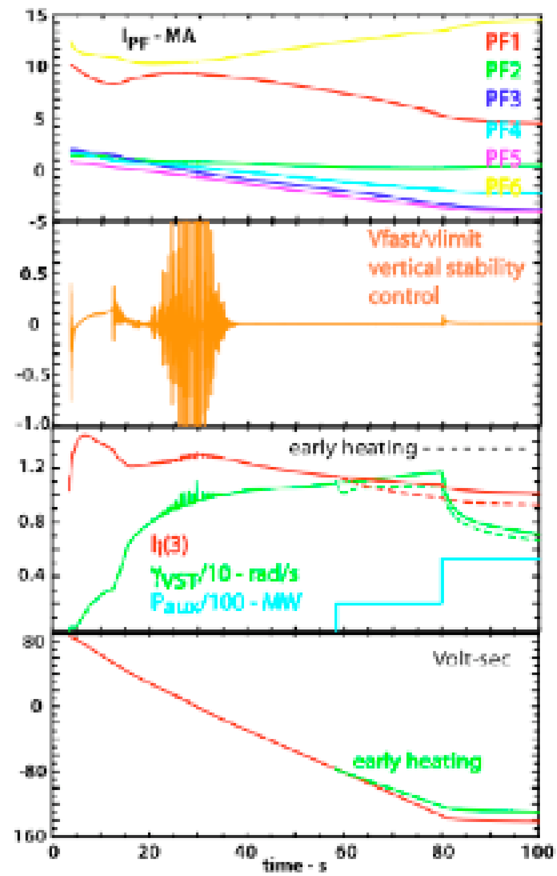
Silicon dumbbells

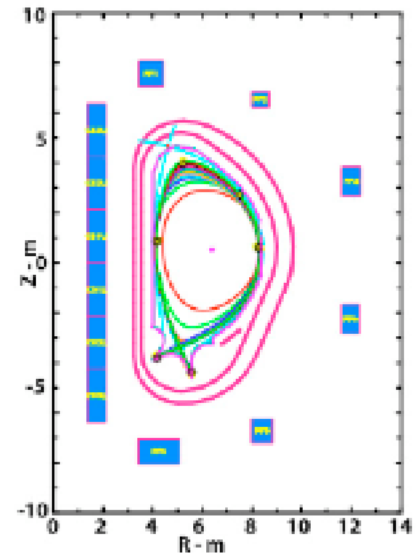
Our plasma control expertise has been of high value in answering ITER design review questions

- Clarified requirements for PF coil system and plasma startup

- **There is also a potential IFE/MFE opportunity regarding ITER control:**

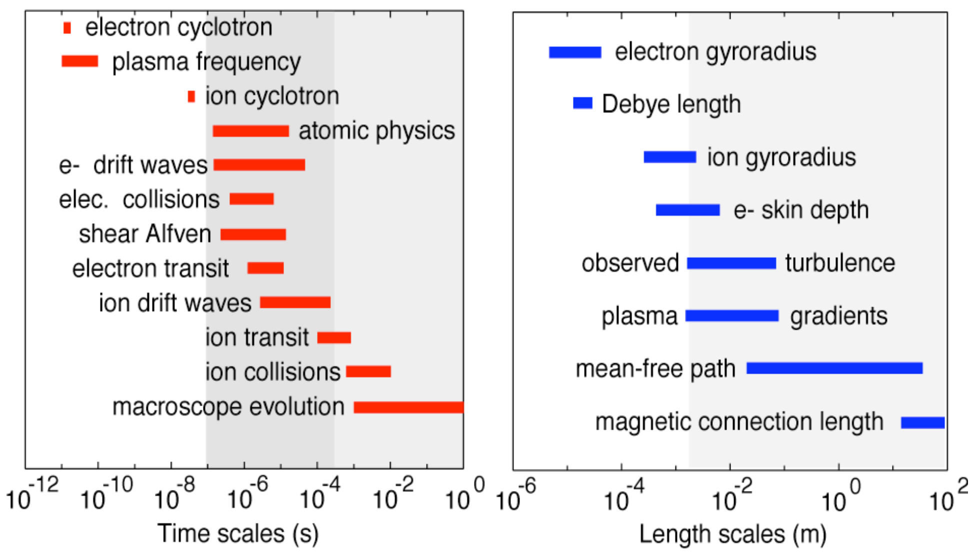
  We've discussed the NIF control system to ITER management (L. Lagin). There is interest in continued discussion

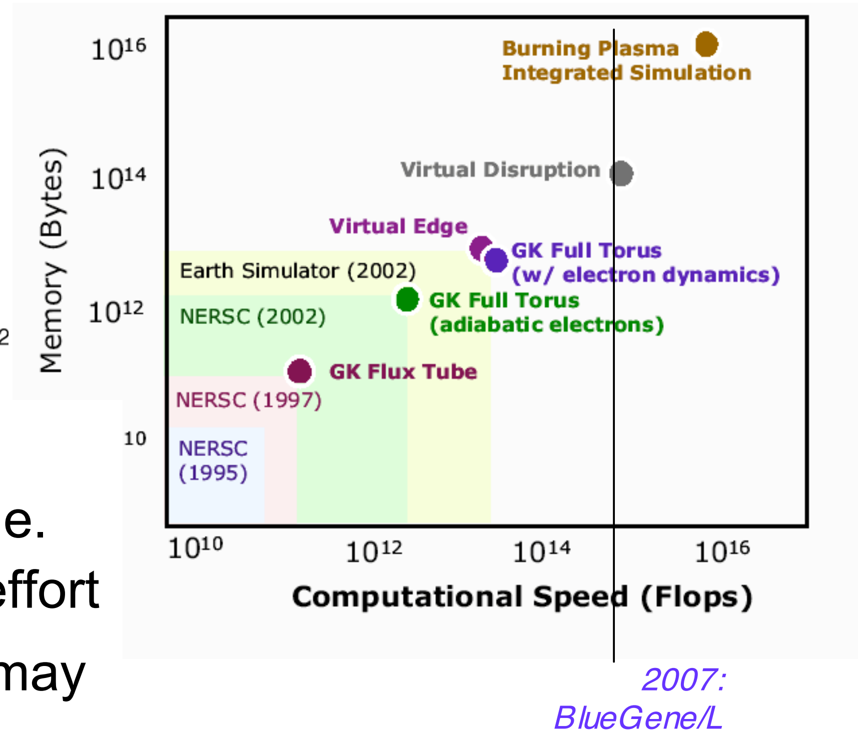




Grand challenge for magnetic fusion: simulate a burning plasma with a validated model that captures the relevant multiscale physics.

Doesn't the ICF/IFE community have a lot to offer in this challenge of multiscale integrated simulation?





- **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

"Greenwald Gap": Predictive Capability

So here is what I say to our LLNL Fusion Energy Program: *The MFE Opportunities are IFE opportunities as well, and vice-versa*…

- Position our experimental and theory work to capture the opportunities in the Greenwald Priorities Report - our boundary emphasis puts us in a great position

  MFE gaps in materials science have strong overlap with IFE needs

- Work with the community in defining an FSP. Explore leveraging the laboratory's expertise in V&V from the ASC community. Explore how lab computing can be a resource for a national FSP effort.

  There is a wealth of experience in ICF/IFE in multiscale integrated simulation expertise that can contribute to this

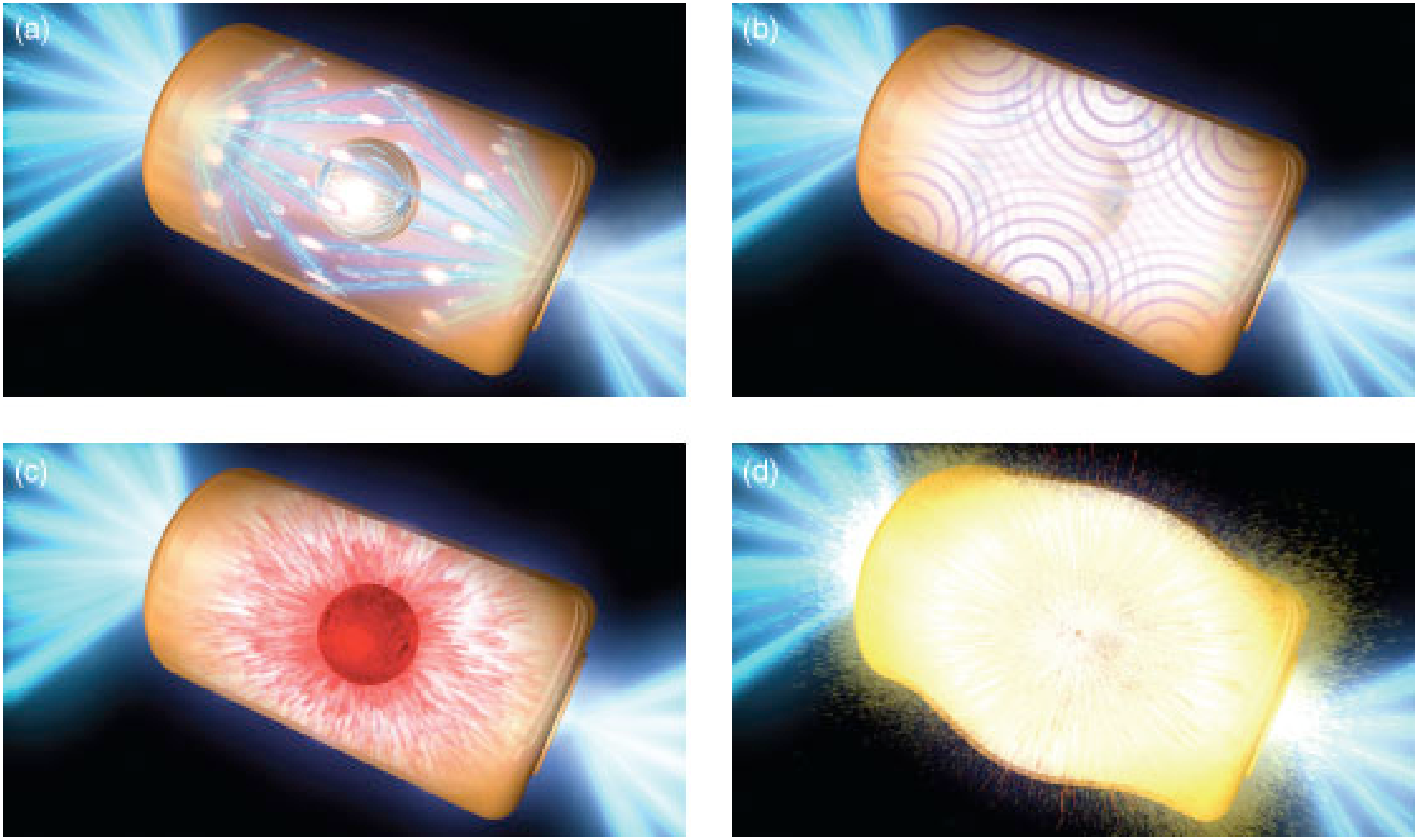
- For the longer term: Explore how FEP can lever its capabilities with expertise in CMELS and SuperSTEM to strengthen our hand in a major next U.S. initiative

  Of mutual benefit to MFE and IFE as well

- Be aware that ITER is enormously complex and first-of-a-kind politically as well as scientifically. It may come calling on the lab's engineering and control system expertise

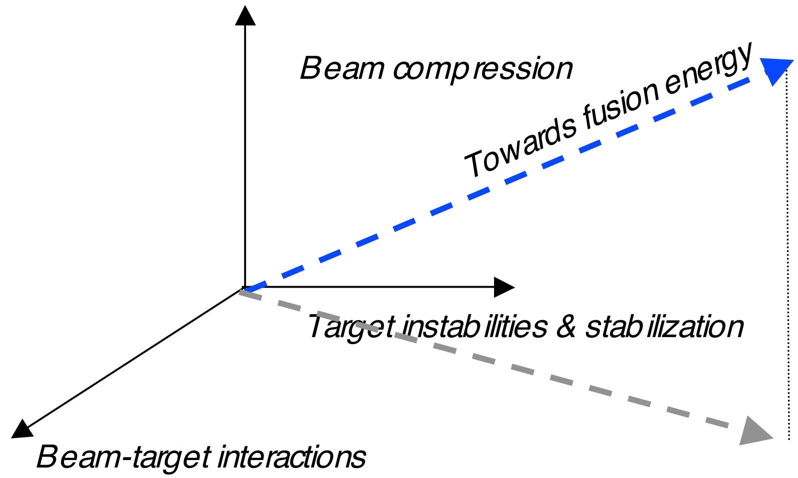
  Here NIF may be of direct benefit to ITER

NIF ignition will provide an enormous opportunity for fusion energy, the lab, the FEP, and the science of HIF



On how we have to frame the heavy ion fusion challenges…

- While OFES has to speak a language that is a "scientific basis set" while we are in the Office of Science, there are plenty of opportunities for moving forward

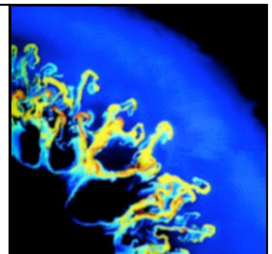
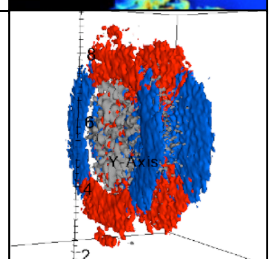
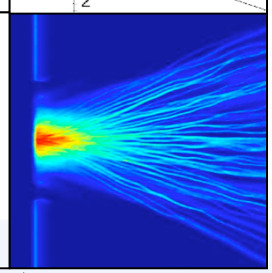


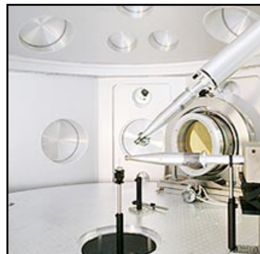
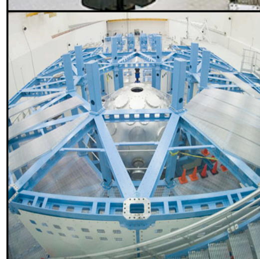
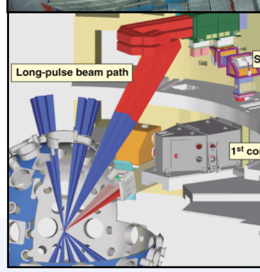
- and you've identified many of them

The LLNL FEP has a new short-pulse HEDP program that leverages NNSA facilities and is designed to provide the tools for modeling fast ignition physics

Create an <u>experimentally validated</u> modeling platform that can handle all of the necessary laser-plasma interaction physics required to support and design the next generation of HED and FI experiments at NIF ARC scale

State-of-the-art codes ⟺ **Experimental benchmarking**

State-of-the-art codes	
3D Rad-Hydro code—HYDRA Hydrodynamics, radiation transport, EOS, ionisation	
3D PIC code—PSC Relativistic laser absorption, electron generation, electromagnetic fields	
3D Hybrid-PIC—LSP Self-consistent electron transport, field generation, large-scale plasmas	

Experimental benchmarking	
	**TITAN** LLNL 200J, 0.5ps in 1 beam
	**OMEGA EP** LLE 5.2kJ, 10ps in 2 beams
	**NIF ARC** LLNL 10kJ, 10ps in 8 beams

NIF ignition will create an opportunity, but several elements need to be in place to capture it

- HIF needs a strong scientific storyline to follow. In the U.S. that still must originate with HEDLP, and this may be the case after NIF ignition as well

- HIF must be seen as relevant to NIF. It must be made clear that it benefits from ignition.

- The HIF community has to remain vigilent in engaging the laser fusion community regarding an IFE vision after NIF

- Need vested interests: We need to keep up efforts to have other communities cheering for HIF's success

You are doing the right thing: you have a credible plan to advance HIFS following NIF ignition

Twenty-year science campaign for heavy-ion-beam-driven HEDP and fusion research

Science Area	FY06 FY07	FY08 FY09	FY10 FY11	FY1 FY13 FY14 FY15 FY16 FY17	FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25
Beam-Target Interaction	Target design + fast beam /target diagnostics	Beam dE/dx WDM experiments	Initial beam-cryo D2 target interaction	Operate IB-HEDPX WDM user facility: EOS, critical points, metal-insulator transitions for many materials	Operate IB-HEDPX WDM user facility: Physics of WDM phenomena relevant to NIF high yield and future FTF fusion chambers
Focusing onto Targets	Larger plasma source	High B focus with time dependent corrections	Double pulse target interaction	Ion planar direct drive hydro experiments with shaped double pulses	Optimize targets with pulse shaping in ion beam direct drive using ten-pulse bunch trains
Longitudinal Beam Compression	60x compression	Compression with 20x transverse focusing	Compress and focus pulse-shaped ion bunches	Optimize compression and focusing using double-pulse beams	Optimize compression and focusing using ten-pulse bunch trains
High Brightness Beam Transport	E-cloud in: 4 quadrupoles 4 solenoids	Beam steering and brightness	Perpendicular and parallel brightness in double pulses	Optimize perpendicular and parallel beam brightness with double-pulse beams	Optimize perpendicular and parallel beam brightness with ten-pulse bunch beams
Advanced Theory and Simulations	Advanced source to target models	Advanced source through target models	Begin direct drive/ multi pulse models	Further develop and apply multi-pulse beam acceleration/ focusing models for both direct and indirect drive	Integrated accelerator beam dynamics with target hydro modeling
Facility & resource needs (Constant $ estimate)	1. Operate NDCX 2. Assemble NDCX-II **$8M/yr tot.**	1. Operate NDCX I 2. Operate NDCX-II **$10M/yr tot**	1. Operate NDCX-I 2. Upgrade II to IB-HEDPX **$16 M/yr tot**	1. Operate IB-HEDPX and support users ($20M/yr) 2. Construct heavy ion target implosion HEDP physics facility ($20M/yr) **= $40M/yr tot.**	1. Operate IB-HEDPX and support users ($20M/yr) 2. Operate heavy ion implosion physics facility (20M/yr) 3. Target & chamber R&D needed for FTF ($20M/yr) **= $60 M/yr tot.**

First heavy ion WDM experiment @ < 1 eV

1 eV in WDM targets; basis for IB-HEDPX

NIF National Ignition Campaign

Begin implosion symmetry tests in NIF of four successive no-yield capsules on the fly to understand precision requirements for IFE (TBD, not included in this budget)

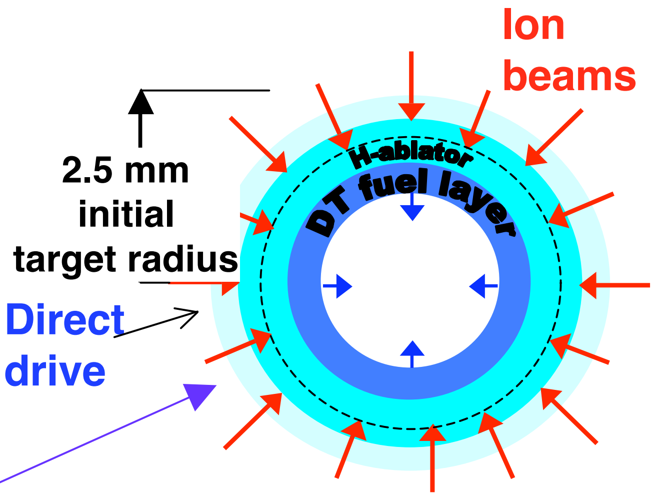
20yr Objective: Develop the beam and HEDP target physics knowledge base for a heavy-ion fusion test facility (FTF)

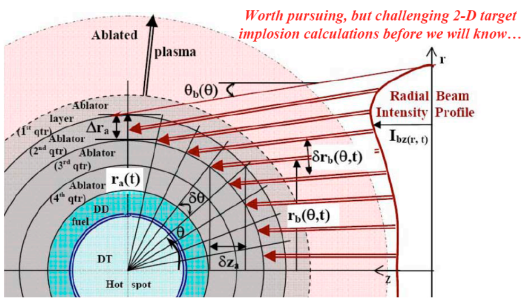
The Heavy Ion Fusion Science Virtual National Laboratory

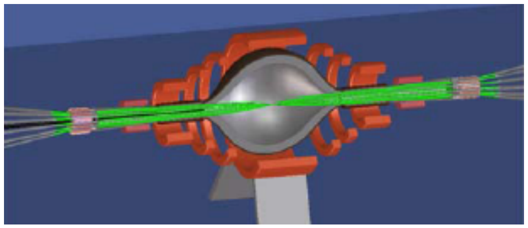
- *A challenge is one of building coalitions* and getting others to root for your success - and to fight for you when you are in tough times
- Offered here: get into the dialogue regarding
  - *- LIFE*
  - *- Materials*
  - *- Integrated modeling*
  - *- International coalitions*

The new direct drive studies are part of a strong science story that continues to develop in heavy ion fusion

<u>New, leading example: Ion direct drive potentially game-changing for IFE</u> - promise of increasing efficiency to 25% by ramping driver energy to penetrate outgoing ablator.
==> reduction in driver energy from 7 MJ to 1 MJ

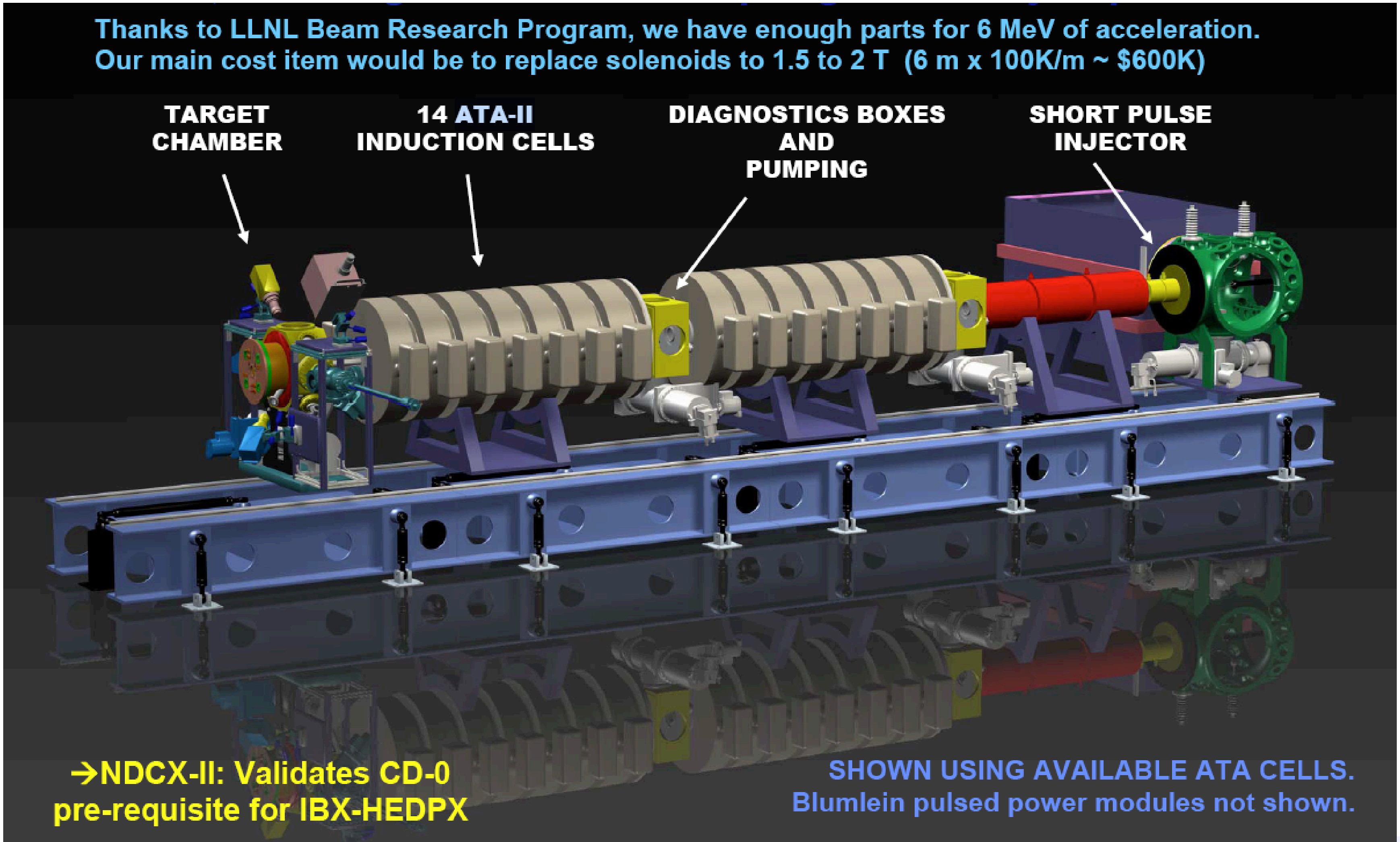






Polar direct drive analysis is promising as well ==>> two-sided illumination

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

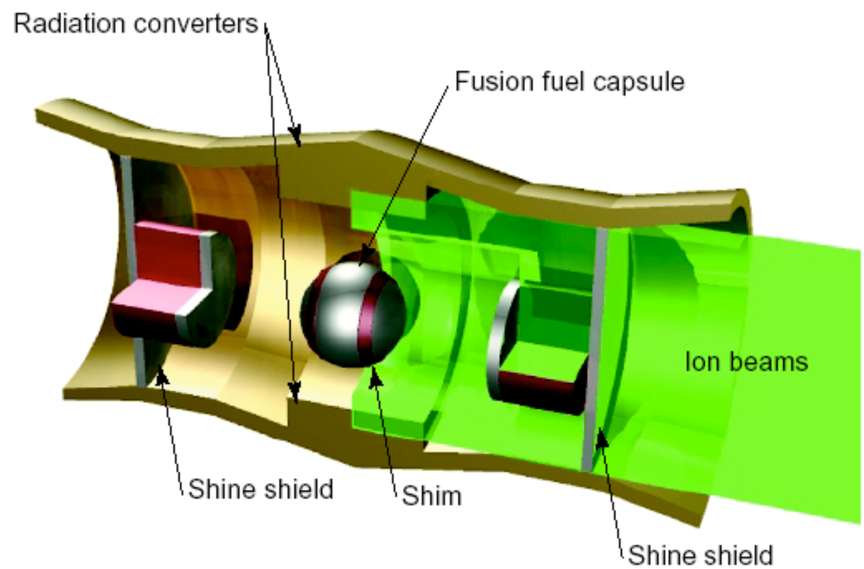


Heavy ion fusion will benefit from NIF ignition…

Success with indirect drive will validate much that is relevant to indirect drive heavy ion fusion

- HIF targets

- But NIF may have an interest in exploring direct drive as well - how does this community engage given your new interests in this? Is there an opportunity with Omega as well?

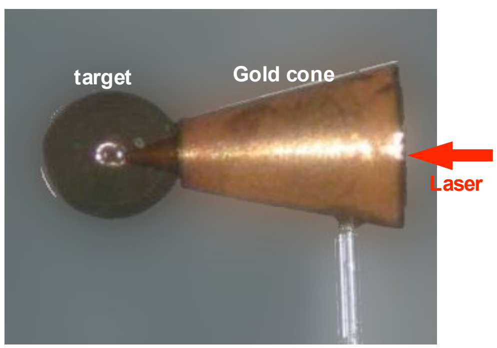


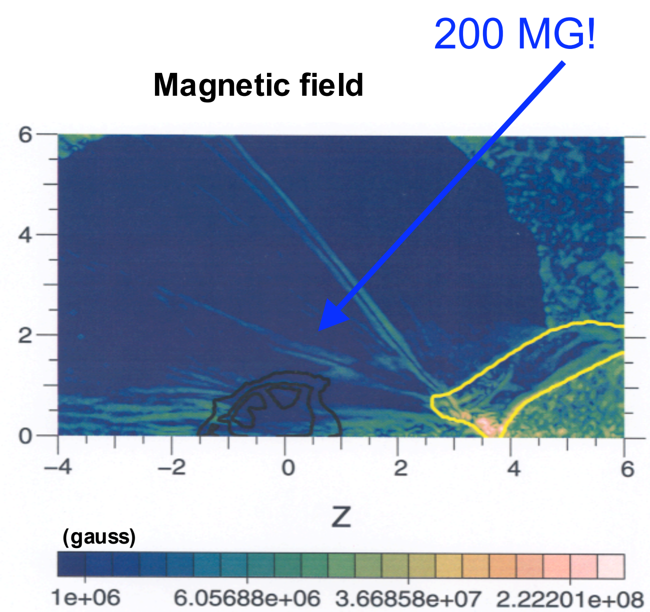
… and can you articulate how you are important to NIF ignition and LIFE?

e.g. Callahan & Tabak, Nuclear Fusion 39, 883 (1999)

… HIF research is indeed giving to other branches of IFE science…

Example: new particle mover for HIF benefits fast ignition: Enables faster simulation of particle motion with large grad-**B**. Alternative to MFE gyrokinetics?





Can such synergies be strengthened?

The "elephant in the room" is how a major next-step will be taken in IFE

- Cost drives approaches in U.S. "big science." ITER as an international approach is a leading example of this.

- The Office of Science is ***<u>keenly</u>*** interested in seeing a successful outcome for the ITER model for doing research…

My own view: a major next step in IFE may well be an international one

- Regarding lasers: NIF, LMJ, a Chinese NIF-like system, HiPER, FIREX, FIREX-II, High Average Power Laser work- all form an impressive set of building blocks for a coordinated international HEDLP/IFE science program

- Regarding heavy ions: you also have the building blocks for a coordinated international effort
  - HIFS-VNL (U.S.)
  - KEK (Japan)
  - GSI, with planned upgrade (FAIR) (Germany)
  - ITEP (Russia)

A challenge is identifying the scientific questions and the complementary roles and responsibilities of the different parties - a collection of facilities does not make for a viable program alone

Is there a model to be developed for an even stronger coalition in heavy ion fusion research?

How would such a community develop other vested interests?

Connectivity to other communities is critical for the success of IFE and heavy ion fusion

- **Leverage** - the IFE and MFE community must work together better than they have. A major opportunity exists in materials science

- **HIF can go far towards energy with the language of science** - In general, fusion needs to do a better job in projecting our development needs onto a “scientific basis set.” The Office of Science will support this approach. I should say that the HIFS-VNL has set a high standard for making these arguments.

- HIF needs to clearly and publicly benefit from NIF, and needs to give to NIF-related science where it can

- **Consider an international approach to take HIF to the next level internationally**. Clearly you understand the potential for this, given that you are all here! I am asking if there is an additional step forward in working internationally that the HIF community can take and thus lead by example.