Overview of the Tritium research activities at LLNL

Presented at the Tritium Focus Group Meeting

May 5, 2015

Susana Reyes and Tom Kohut
Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory

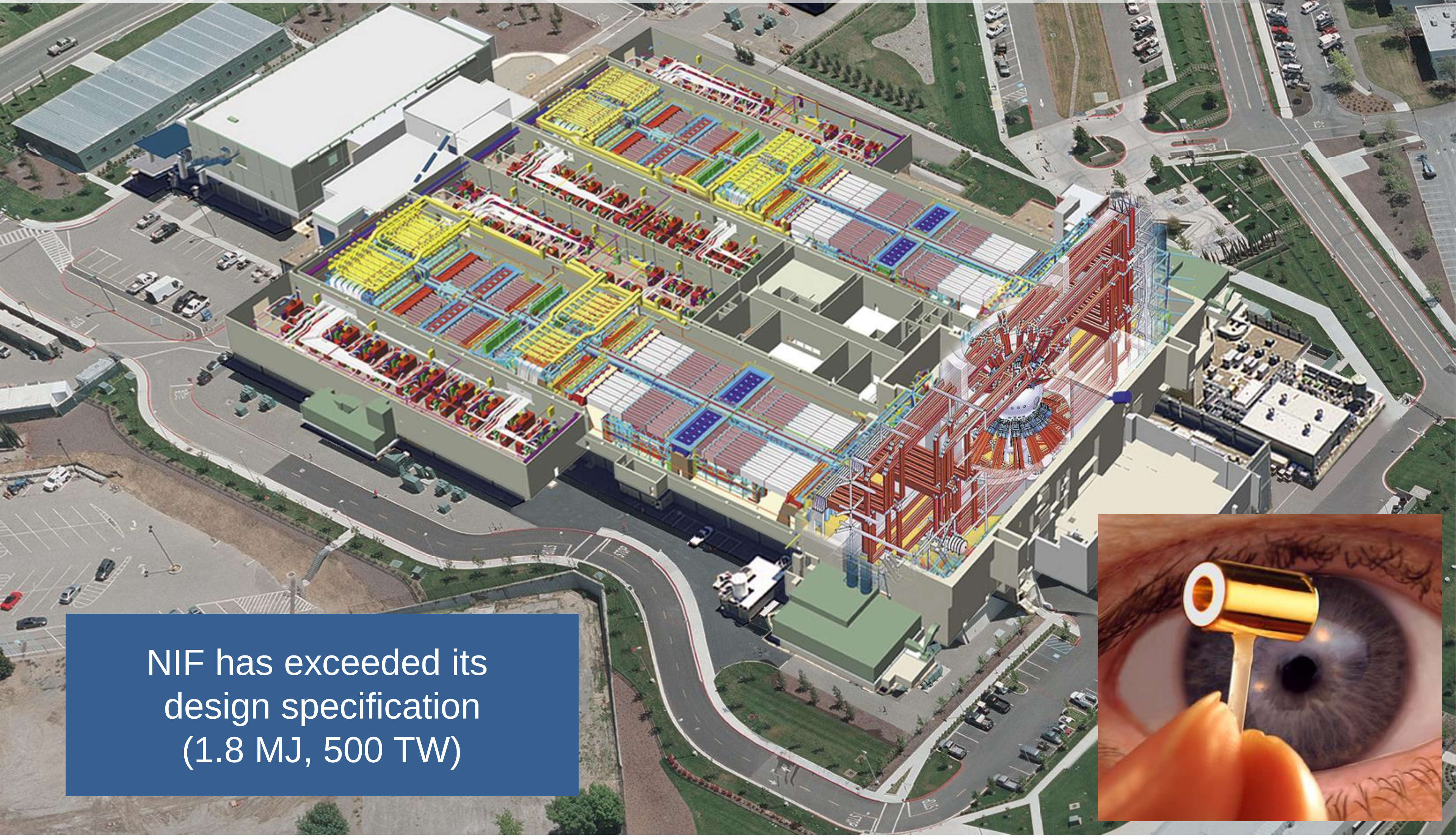
LLNL-PRES-XXXXXX
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Outline

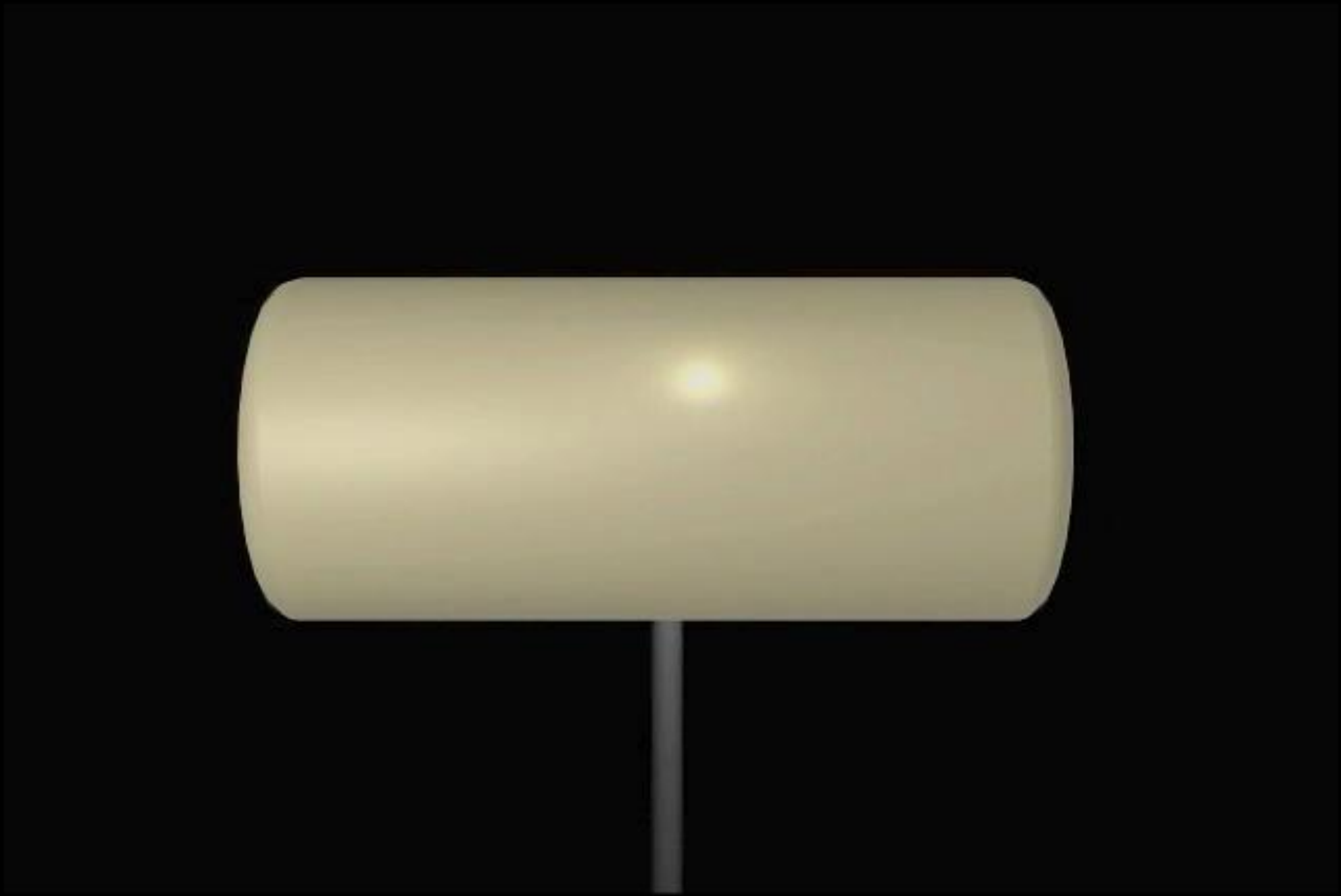
- Introduction
- Overview of tritium usage at NIF
- IFE tritium and fuel cycle research activities
- Future directions


San Francisco
(45 mi.)
LLNL
National Ignition Facility
NIF-0605-10997-L1
27EIM/cld

NIF is a football stadium-sized facility that concentrates the energy from 192 lasers into a mm^3 target

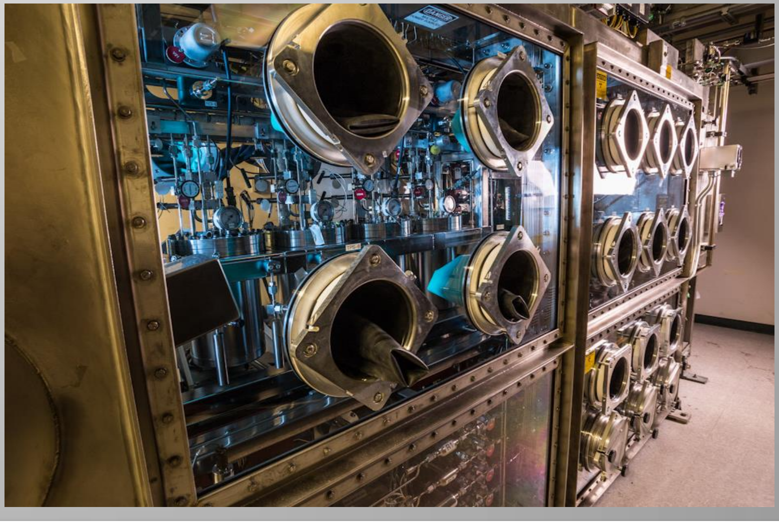


NIF has exceeded its design specification (1.8 MJ, 500 TW)



NIF Tritium “Loop”-Tritium Facility B331 operations

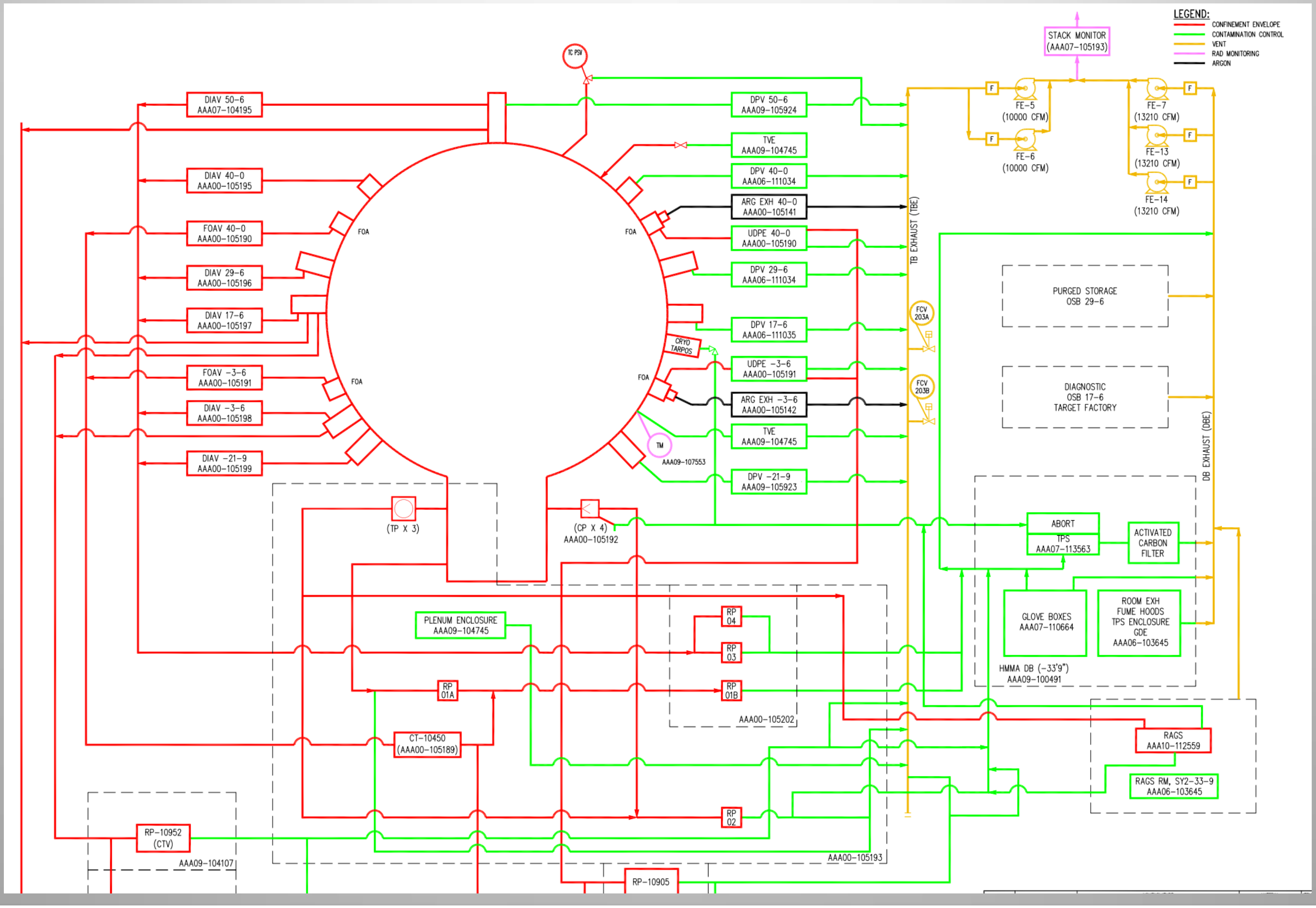
- NIF began tritium operations in Sep. 2010
- LLNL Tritium Facility receives bulk tritium shipments from SRS
- Custom mixes of D/T/H are prepared in B331 glove-box and fill small “reservoirs” for shipment to NIF
  - Each typically contains between 20 and 200 Ci (depending on desired experimental mix, gas density and fielding details)



NIF Tritium Operations

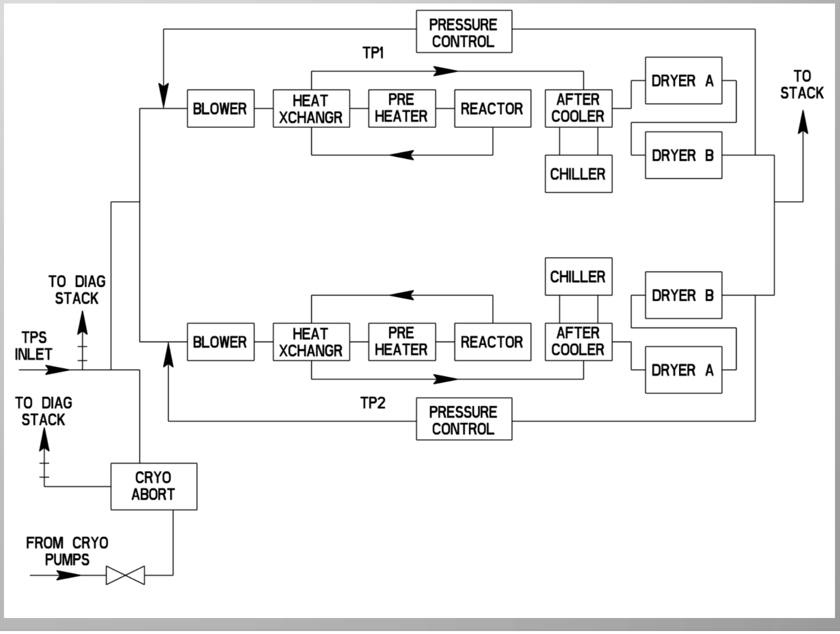
- NIF personnel transport and install reservoirs on target positioner or associated external glove-box
- Ignition target is cooled to cryogenic temp., target is fueled, and ice layer is formed over a several day period (for layered implosions)
- After experiment, excess tritium from target, and vent/pump gas from connected vacuum volumes are directed to NIF's Tritium Processing System (TPS)
- Vacuum volumes sampled (fixed or portable tritium monitors) prior to entry to confirm acceptable airborne tritium concentrations (typically 1-10 DAC)
    - Volumes are then ventilated directly to stack during access and servicing

TPS receives exhaust from all target bay vacuum pumps
Target Bay ventilation is routed to stack



Tritium Processing System

- Accepts effluent from all target area vacuum systems and glove boxes
- Two identical 250 scfm skids; one running continuously and one in standby
  - Suction side maintained at -2 to -4” w.g. pressure; exhaust sent to stack, (HEPA filtered and monitored prior to release)
- Typical catalytic oxidation and molecular sieve capture system
  - System recovery efficiency >99.9%
  - Saturated molecular sieve beds from TPS have mol sieve removed, then disposed of as low level waste; vessels are refilled and re-used
- Annual throughput between 2000- 4000 Ci
- Annual stack releases between 1 and 9 Ci per year (80 Ci limit per EIS)



Tritium controls effectiveness

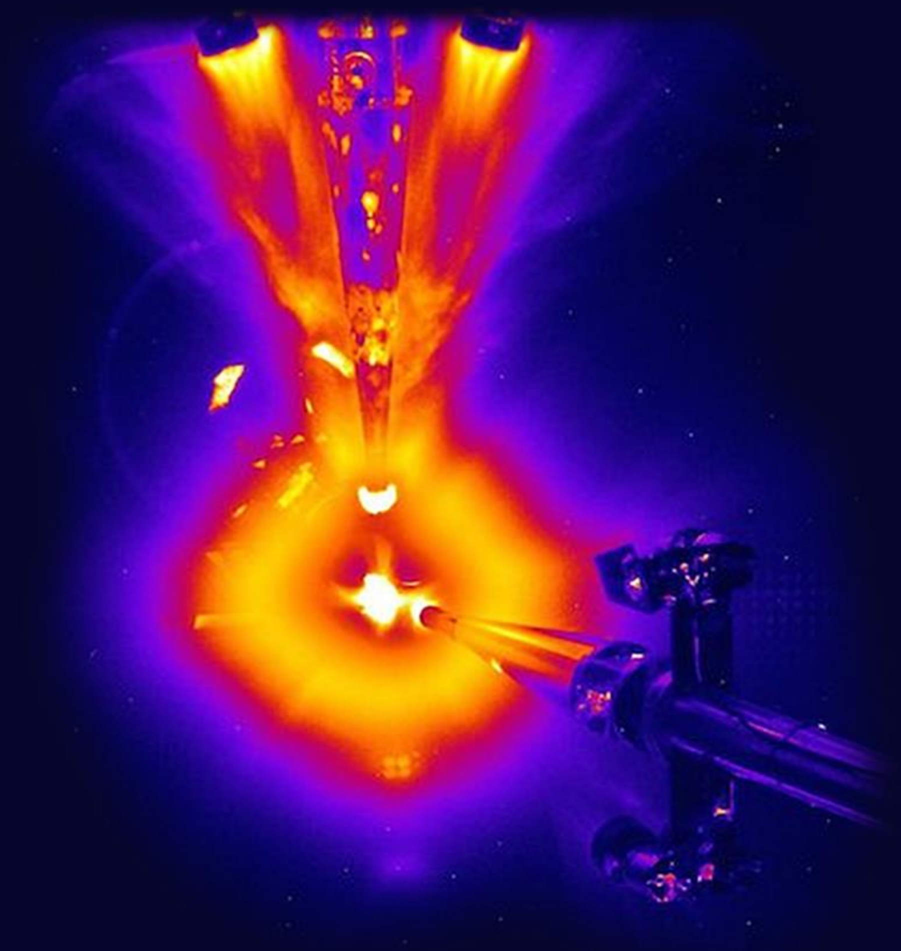
- Tritium controls have been effective
  - No reportable tritium bioassay doses to date (1 mrem TEDE reporting threshold)
  - Stack releases well within EIS limits
  - No surface contamination spread outside of controlled areas
  - Enclosure ventilation/negative air effective at preventing personnel exposures and maintaining surface contamination levels low
    - — Most working areas (inside vessels) <100,000 dpm/100cm^2 most of the time
    - — Individual components and inside of TC range from a few E4 to a few E6 dpm/100cm^2

Removing a molecular sieve bed for reprocessing

Removing a tritium reservoir from CryoTARPOS

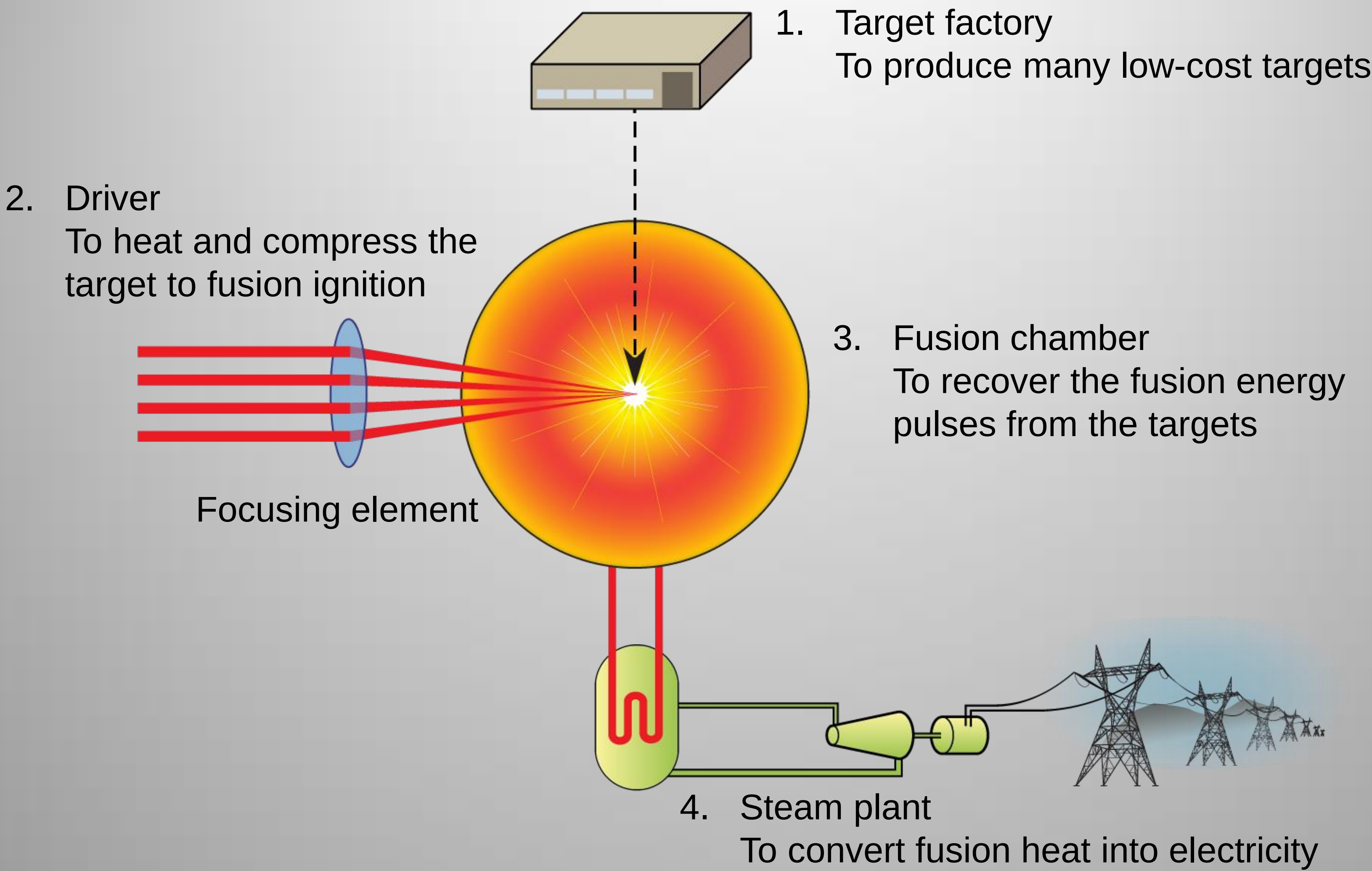
Installing an ignition target

Picture of a target shot



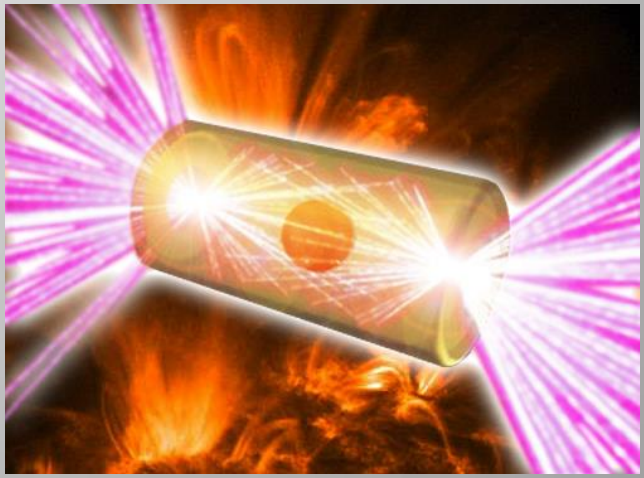
Another reservoir installation in the cryoTARPOS glovebox

Ignition in NIF would represent a key enabling opportunity towards IFE



Fusion's attractive S&E characteristics have long been recognized

- Able to provide baseload power at a global scale
- Power excursions self-limited by inherent processes
  - "Run-away" reactions are physically impossible, unlike chemical or nuclear fuels
- No long-lived radioactivity, or use of nuclear materials
- Reduced environmental footprint
  - Very low lifecycle emissions
  - Potential for economic dry cooling
  - Waste disposal and tritium management
  - Fuel cycle not extractive
  - Efficient land use, and near load-centers
  - Good local air quality

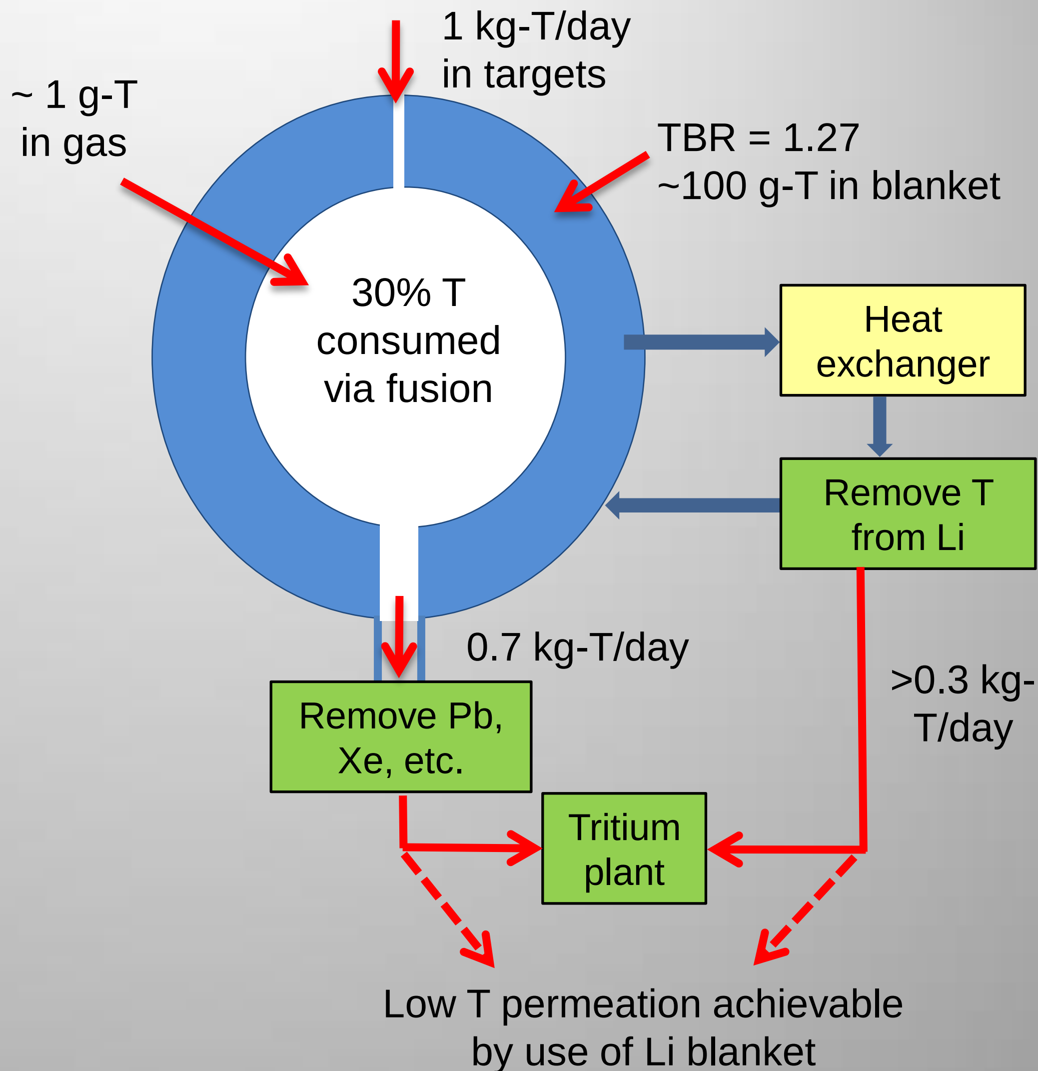


The top-level technical challenges for IFE are well known

1. Ignition and fusion energy gain
2. Fuel system delivery
   — Rapid fuel production
   — Low cost manufacture
3. Durability of the fusion chamber and optics
   — Cyclic thermo-mechanical stresses
   — Resistance to damage and corrosion
   — Optical lifetime in chamber environment
4. Safety and licensing (routine operations, accidents)
   — Tritium and other activated materials
5. High availability plant operations

IFE fuel cycle will process approximately ~1 kg of tritium per day

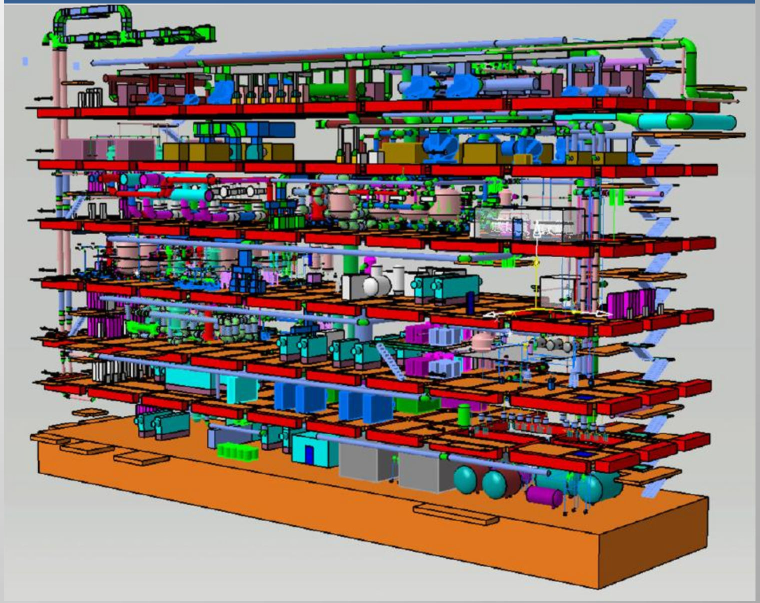
- Important fuel cycle considerations:
  - Fuel burn-up fraction
  - Tritium breeding & recovery
  - Nuclear data/modeling uncertainties
  - Permeation control
  - Tritium trapping/retention



Relative scale of IFE tritium processing systems

	ITER	MFE-DEMO	IFE-DEMO	IFE - Full
Fusion power (MW)	500	2700	1100	2200
Fueling rate (kg/hr)	1.1	1	0.03	0.06
Fueling rate (g/day)	25333	20600	735	1356
Burn fraction	0.003	0.02	0.23	0.27
T consumption (g/day)	76	412	169	366
T recovery (g/day)	25257	20188	566	990
T breeding	<0.4	450	203	439

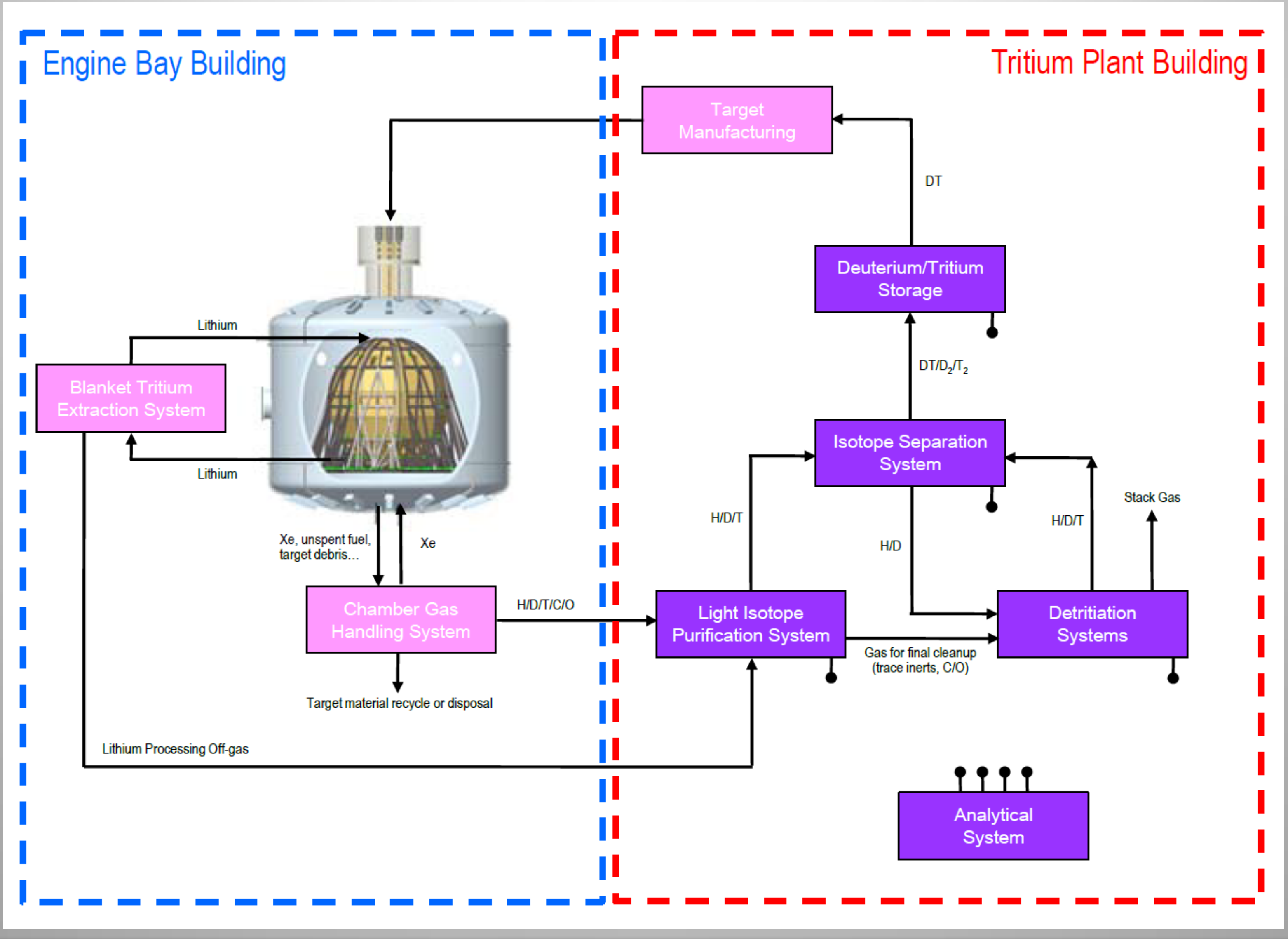
ITER tritium plant
(Glugla et al., ITER Organization)



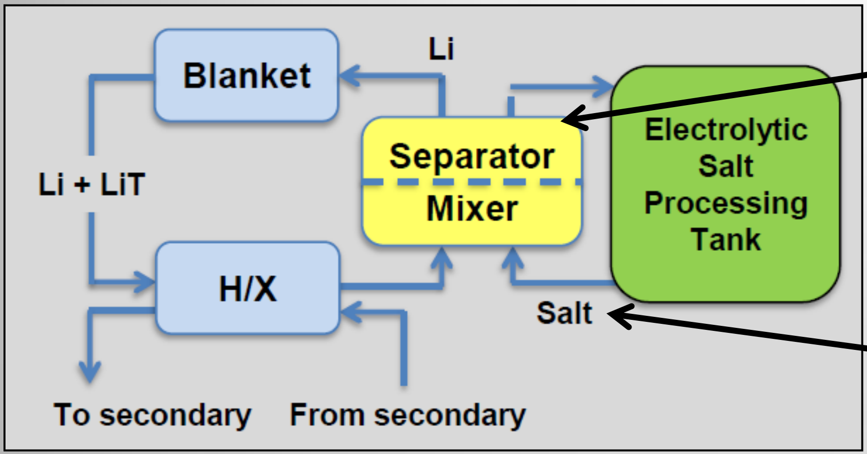
- IFE tritium plant is more compact than proposed previously:
  - ITER systems sized for 200 Pam^3/s of DT~ 100 SLPM
  - IFE systems ~ 8 SLPM
- Reduced flow rates and protium allow for isotope separation via TCAP
- Simpler requirements for storage and delivery towards target manufacturing

IFE fuel cycle design uses design experience at Savannah River, Los Alamos and Livermore Labs

Simplified block diagram of the IFE fuel cycle



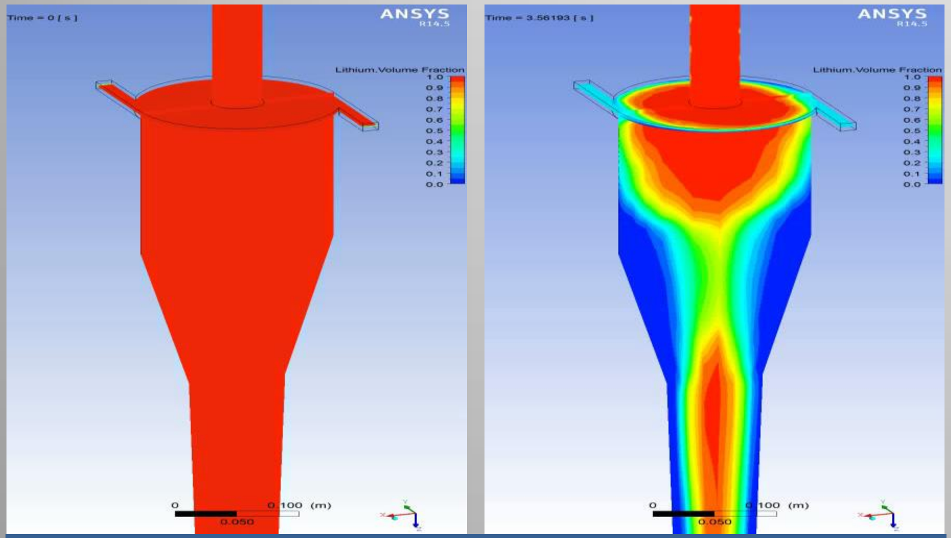
Ongoing work on tritium extraction from fusion blankets



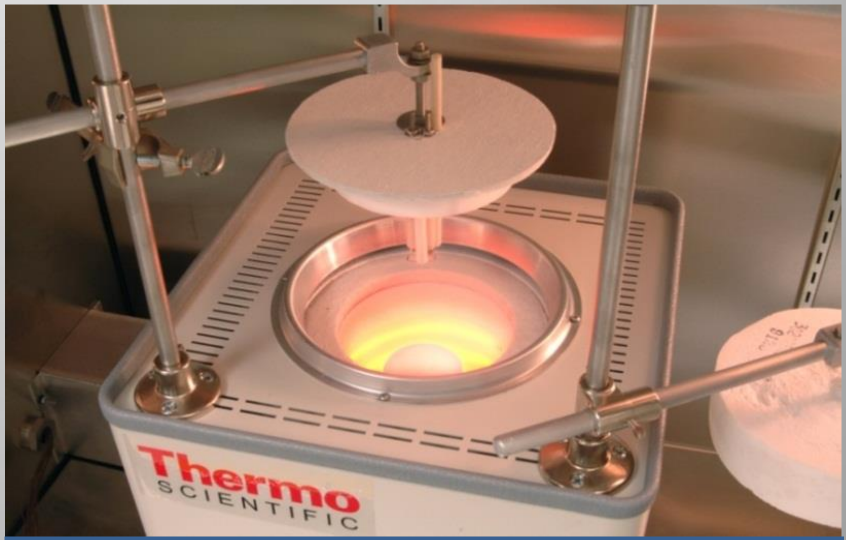
Alternative contactor with no moving parts

Baseline concept for T extraction from Li (Vic Maroni et al., ANL, 1974)

Alternative non-hazardous extraction solvent



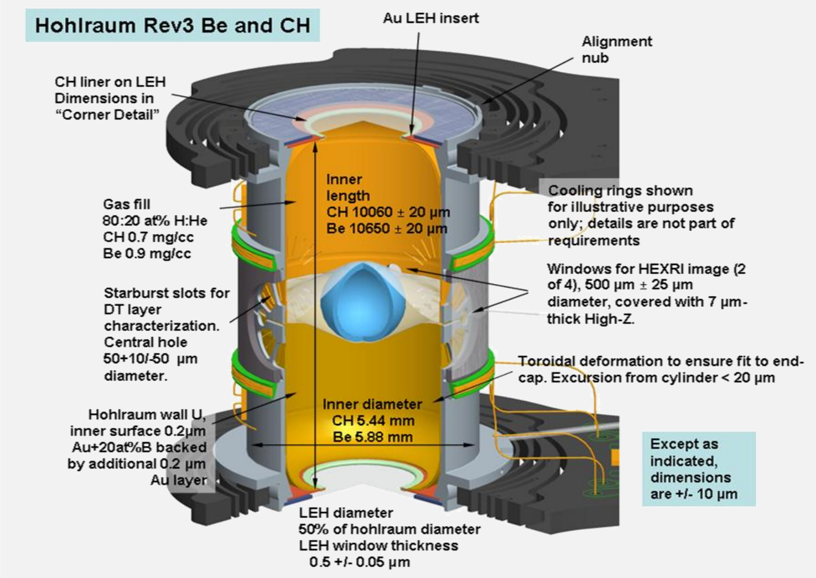
CFD simulations of alternative contactor



LLNL's high-T electrochemical cell

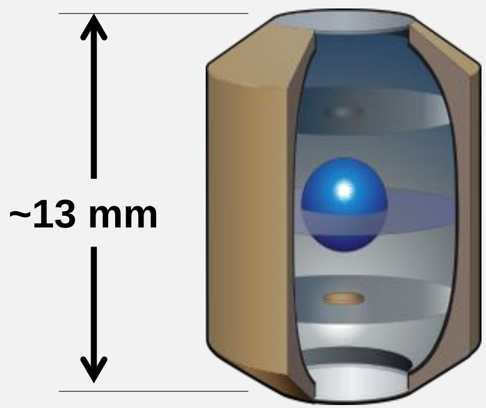
IFE energy requires new target manufacturing paradigm

Target for an ICF Experiment



- Expensive
- Production rate: ~1 per day
- Manual, high-precision fabrication
- Held stationary in chamber

IFE target

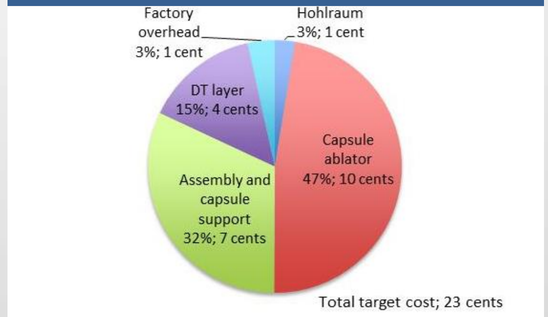


- Low cost (< 50 cents each)
- Production rate: ~1 million per day
- Automated production
- Injected at ~250 m/s for fusion energy applications

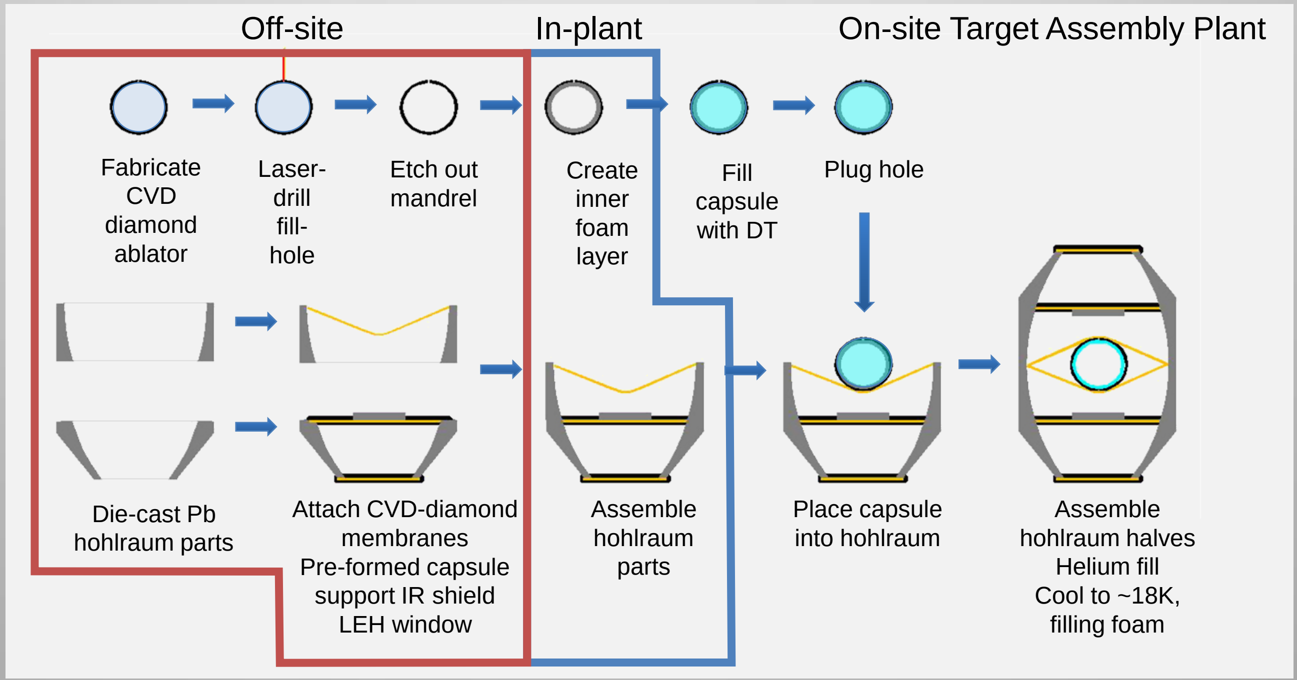
Concepts exist for low-cost, mass manufactured fuel, but development is required

Die-cast hohlraum components

Target component cost breakout



Plasma – CVD HD Carbon Capsule

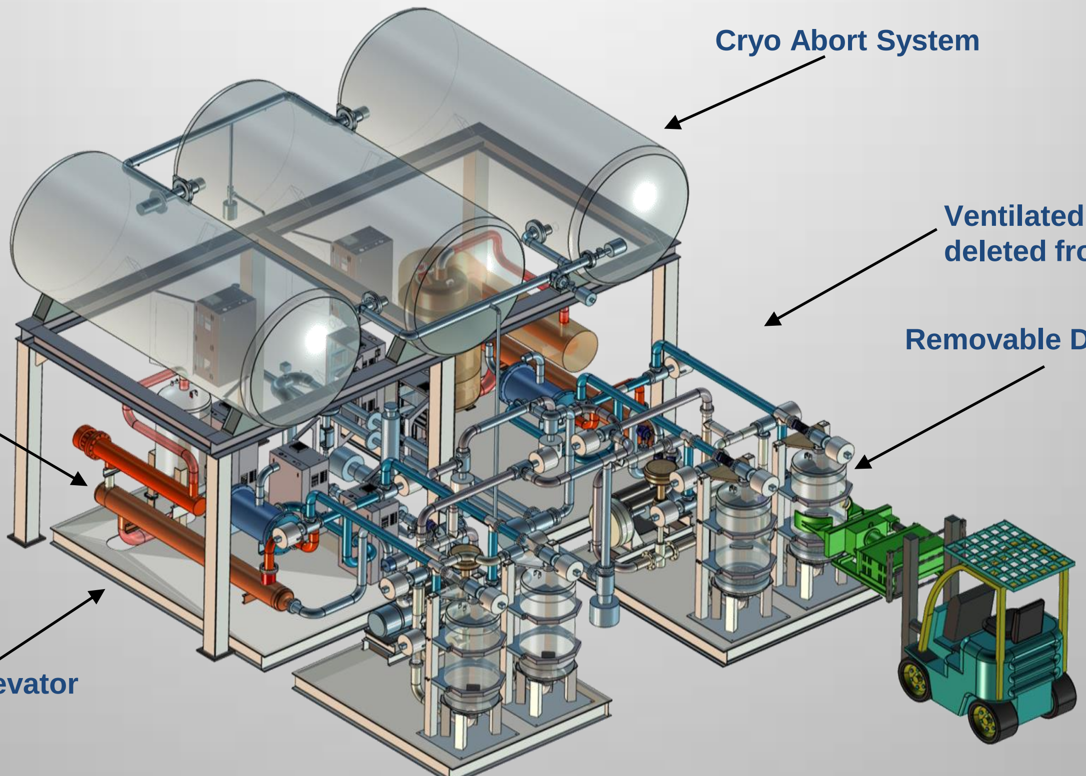


Major conclusions

- Tritium is being routinely used at LLNL for NIF operation
- Efficiency of NIF tritium controls have been demonstrated
- Ignition in NIF represents a key enabling opportunity towards IFE
- A pre-conceptual design of the fuel cycle design for an IFE plant has been completed
- Advancing fusion nuclear science requires additional work is these key areas:
  - Research and development of tritium breeding, extraction and processing technologies for plant-scale systems
  - Minimization of tritium inventories allowing for attractive safety basis and simplified licensing
  - Public acceptance will be the ultimate key for successful fusion energy: control of routine tritium releases is critical for the success of fusion energy

Lawrence Livermore
National Laboratory

The NIF Tritium Processing System (TPS) provides the principal capability for recovery of tritium from target bay operations



TPS will use the well established recovery process involving catalytic oxidation of the tritiated effluent with the resultant water species collected on molecular sieve dryer beds

TPS mol sieve tritium content is important to measuring facility in-process tritium inventory

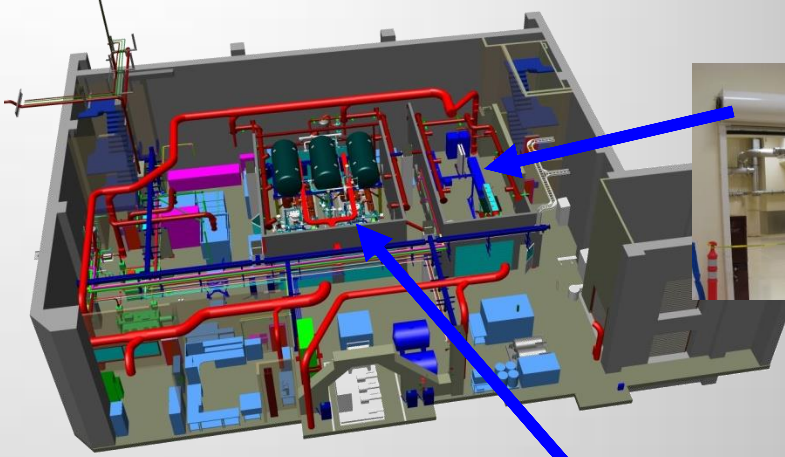
[In process T inventory]=[T in targets]-**[T out TPS]**-[T out stack]-[T out reservoirs]-[T Holdup]

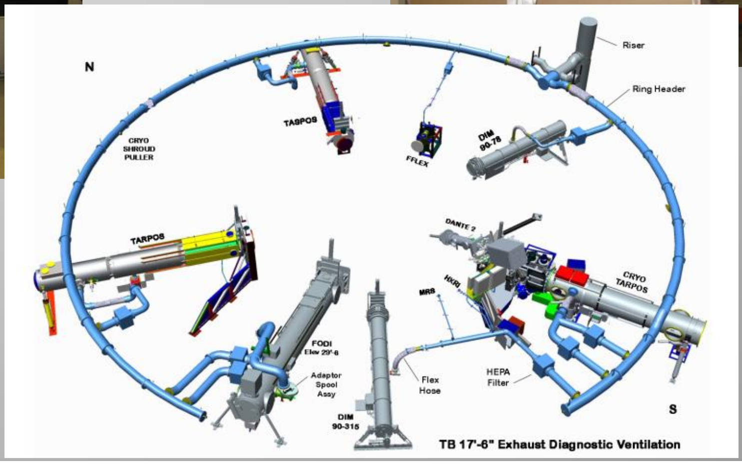
- TPS mol sieve Tritium content estimated by:
  - Integration of (average values of) ([T in]-[T out]) x Flowrate
    - [T] measured on each skid or at combined inlet/outlet headers
      - Skid concentration will normally be lower due to recirculation flow
    - Similarly, flow rate can be measured at either location
      - Skid flows normally closer to full instrument range due to recirculation, but combined headers more accurate at low flow rates
- Strategy: Evaluate accuracy of measurements by:
  - Statistical analysis of estimated accuracy based on reported instrument accuracies (in process)
  - Calculate real time tritium totals based on all instrument combinations to determine which works best
  - Conduct commissioning test using known tritium content and compare to real time accumulations for each instrument combination
  - Send a few removed mol sieves to tritium facility for better estimate of removed total tritium (homogenize and sample pellets and measure average tritium content; combine with weight difference before and after accumulation to estimate total)

Facility working tritium inventory limits will be reduced to account for expected uncertainty

Systems for managing tritium are being installed

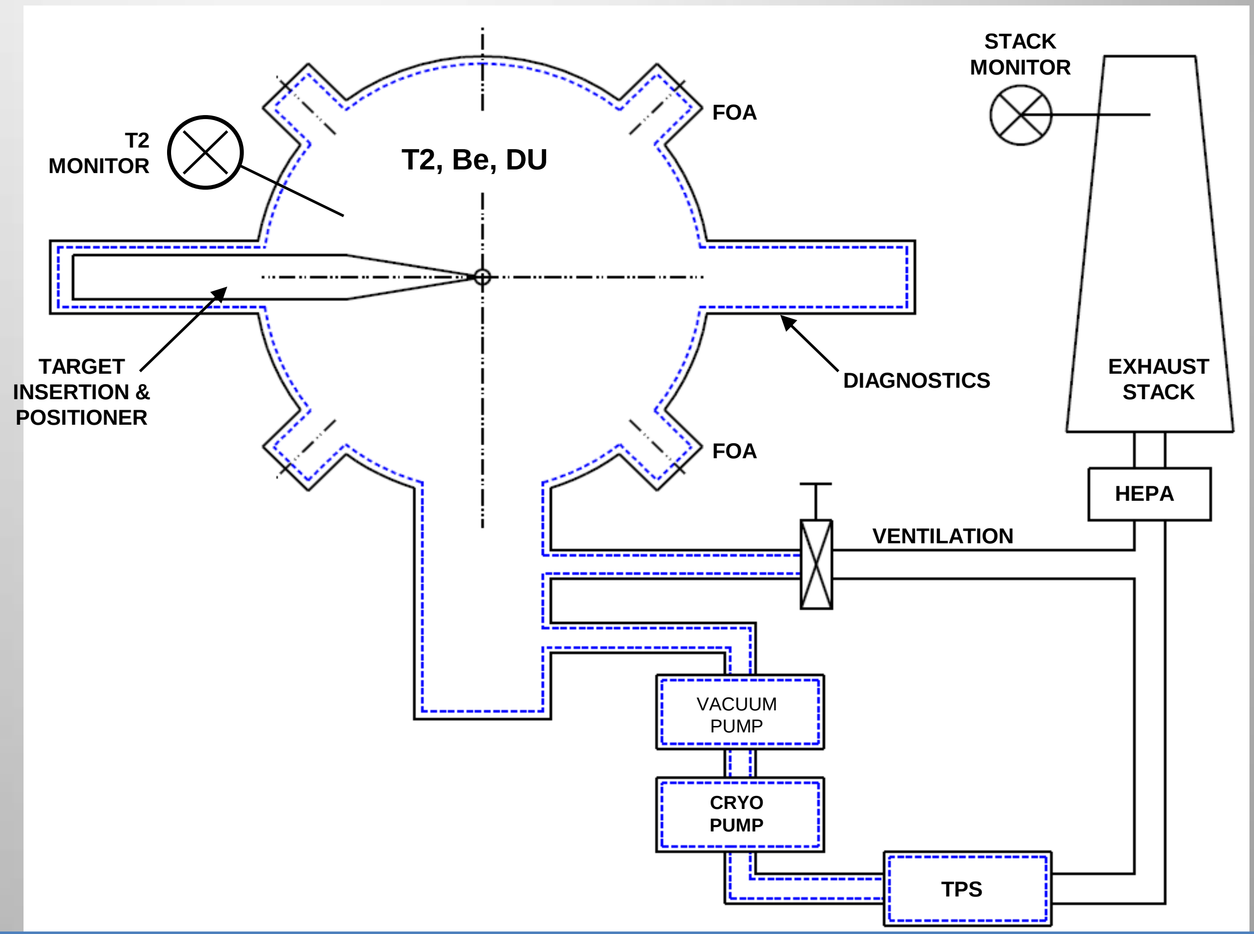
- Hazardous Materials Management Area
- Tritium processing system
  - Effluent from all target area vacuum systems
  - 500 cfm capacity
- Stack, area and process tritium monitors (25 total)
- Diagnostic ventilation systems





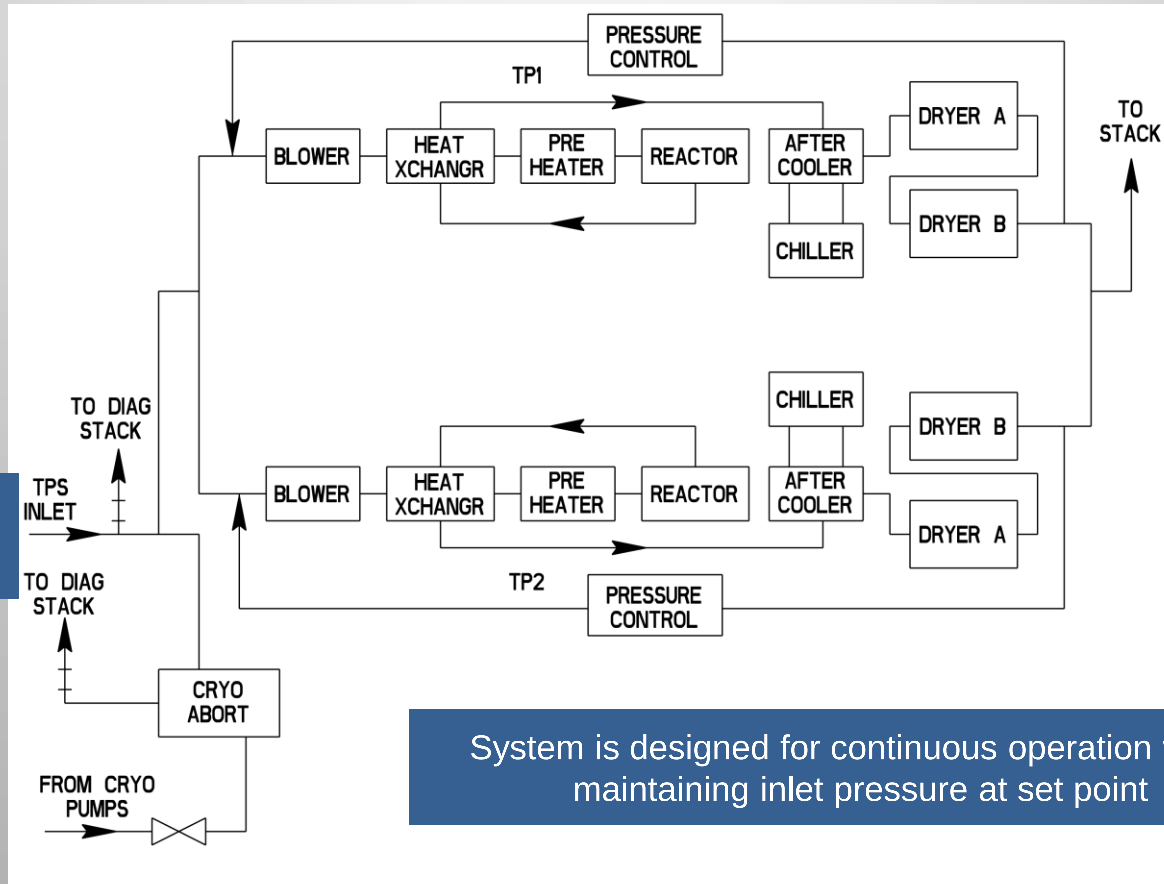
Tritiated effluent from NIF Target Bay operations will be routed to the TPS or exhaust stack depending on tritium concentrations

- TPS Interfaces:
  - Target area roughing pumps
  - Diagnostic roughing pumps
  - Cryo regen roughing pump
  - Cryo TARPOS roughing pump
  - Cryo TARPOS cryo pump
  - Cryo TARPOS glove box
  - TC cryo pumps
  - DANTE cryo pump
  - DIM roughing pump (new)
  - FOA roughing pumps (new)
  - ARC roughing pumps (new)
  - Decontamination area systems
  - Exhaust stack
  - Facility utilities



Tritium monitors associated with the target chamber and attached vessels will provide NIF Operations with routing information for tritiated effluent.

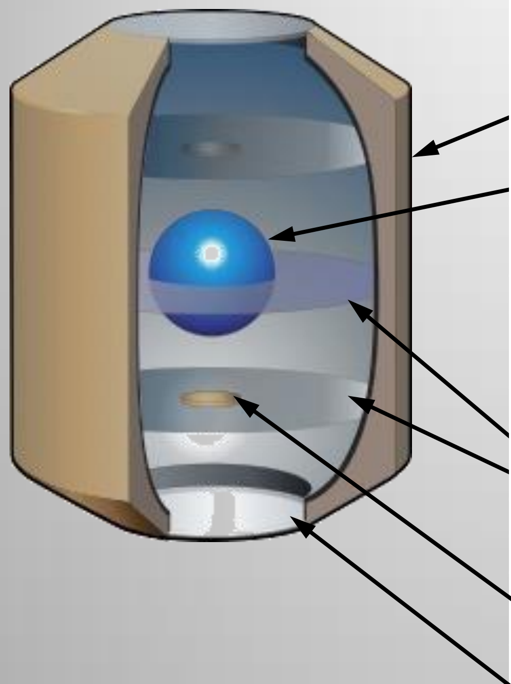
TPS consists of two 250 scfm skids that can be run independently or in parallel (system capacity 500 scfm)



Inlet pressure
- 2 to -4
inches water

System is designed for continuous operation while maintaining inlet pressure at set point

Chamber exhaust characterization is essential for design of tritium systems

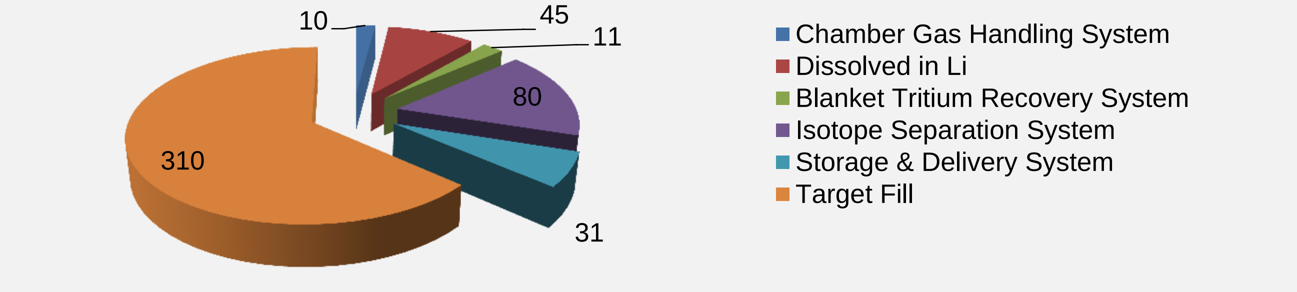


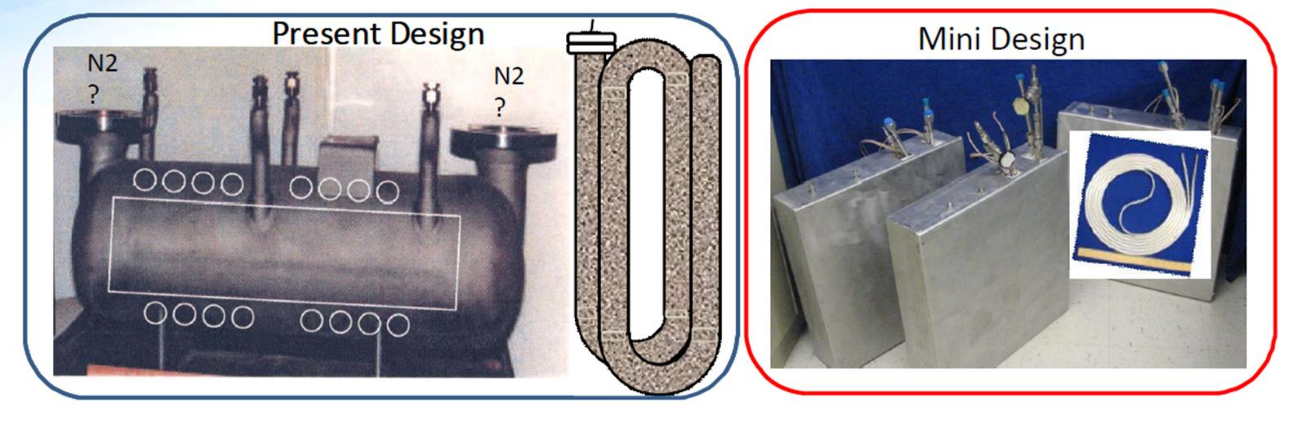
Component	Dimensions	Material	~Mass (mg)
Hohlraum	Length = 1.54 cm ID = 0.89 cm Thickness = 0.05 cm	Pb; 5% Sn or Sb	2579
Capsule			
Ablator	OD = 0.382 cm Thickness = 75 um	C	11.6
Dopant		Ta	0.0021
Foam	Thickness = 142 um	DCPD (< 20 mg/cc)	0.1389
DT	Thickness = 142 um	DT	1.3889
Support	Thickness = 110 nm	C	0.0488
IR window			
Substrate	Thickness = 400 um	C	0.2439
Metalization	Thickness = 30 nm	Al	1.01E-05
P2 shield	OD = 0.191 cm Thickness = 10 um	Pb; 5% Sn or Sb	6.50
LEH window	Diameter = 0.45 cm Thickness = 500 um	C	0.2439
Total mass			2599

- Optimized IFE target design eliminates CH substrate (no protium)
- Tritium per target < 1 mg (~ content in one EXIT sign)
- Exhaust is composed of chamber gas (Xe), Pb, and other target materials in trace amounts

Recent advancements in tritium technology enable compact architecture and lower tritium inventory

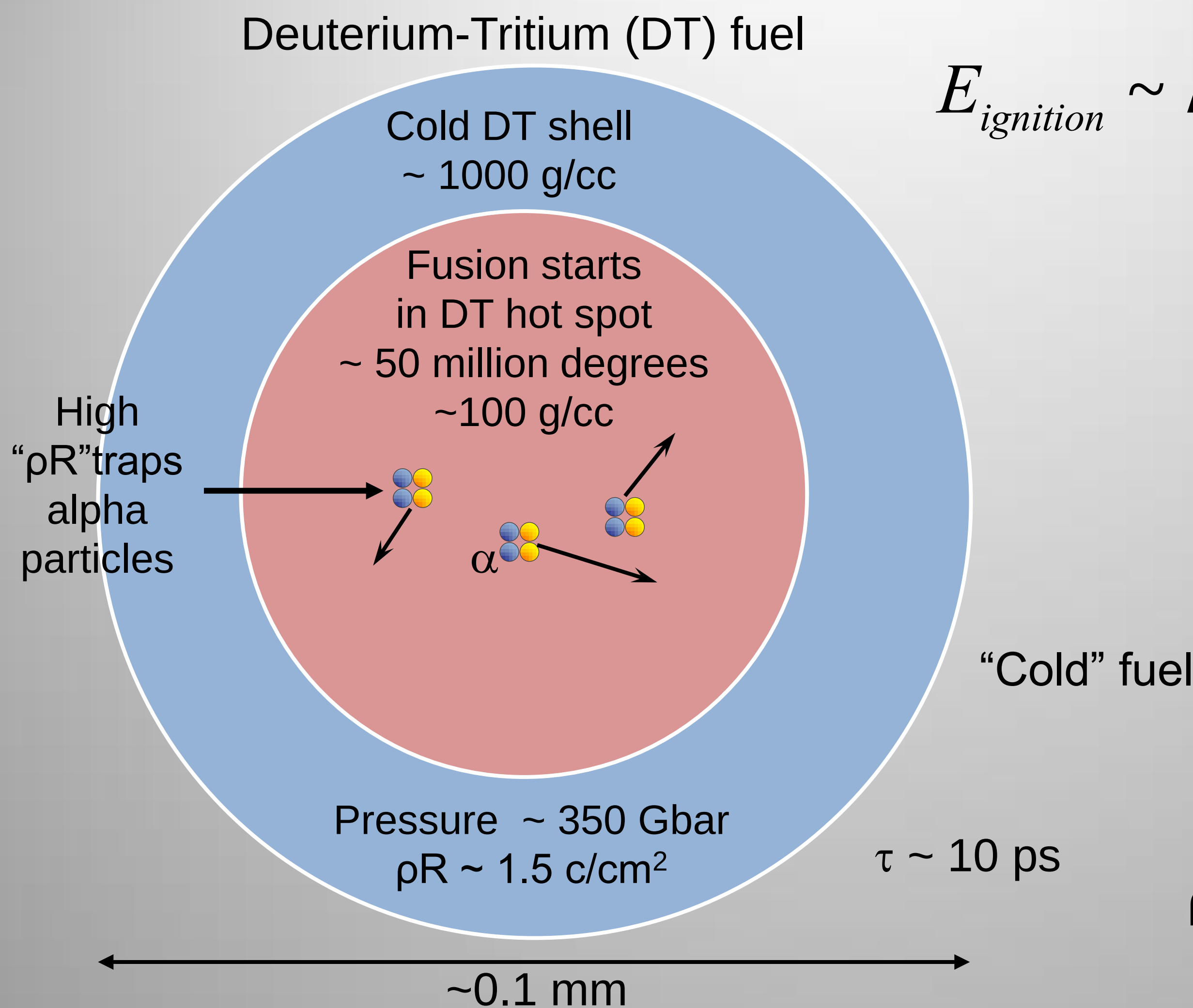
Minimization of tritium inventories is key to maximize fusion's S&E potential





Examples include SRNL's micro- TCAP technology and use of cryo-viscous compressors for fusion power plant

Ignition on NIF requires pressures ~ 350 Gbar and densities ~ 1000 g/cc

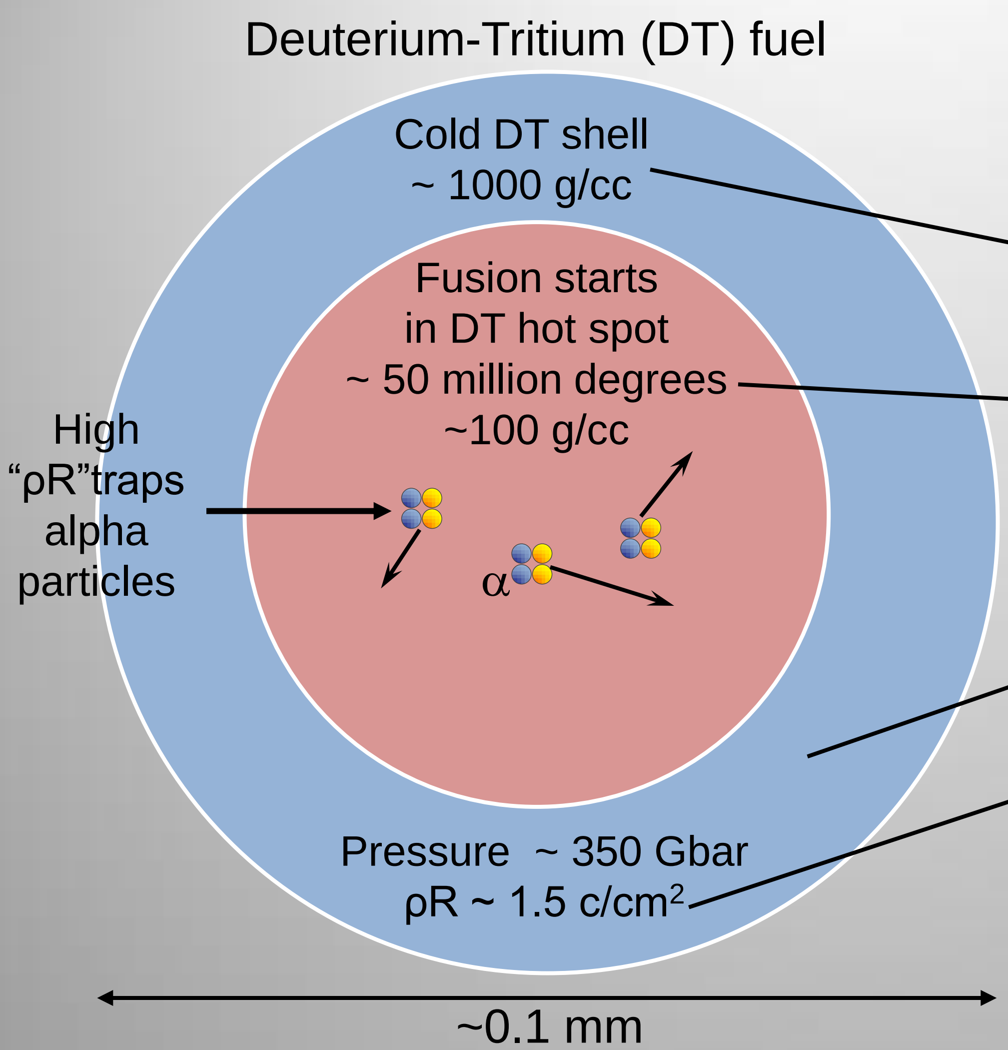


$$E_{ignition} \sim r R^3 T \sim \frac{(r R)^3 T^3}{P_{stag}^2}$$

$$P_{stag}^2 \sim CR^6$$

ρR = Areal density

Conditions are currently ~ factor 2 from ignition



Best performance on single shot

~ 27kJ (2X from alpha heating)

~500 g/cc

~40 g/cc

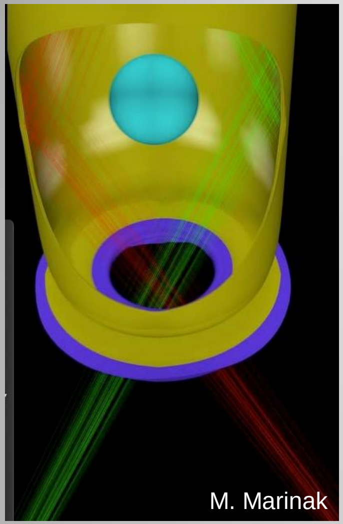
~ 5 keV

~150 Gbar

~0.75 g/cm^2

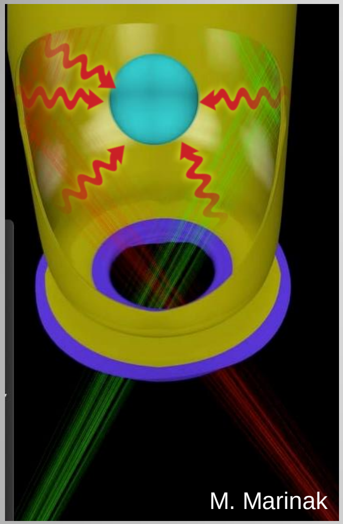
CR ~ 35

ρR = Areal density



E_{laser} ~ 1.8MJ
$E_{X\text{-}ray}$ ~ 1.3MJ

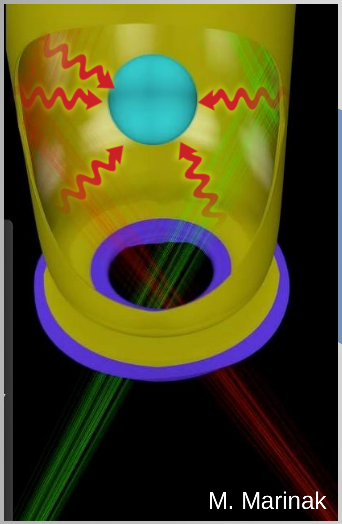
~60-70%



$P_{ablation}$ ~ 100 Mbar

E_{laser} ~ 1.8MJ
$E_{X\text{-}ray}$ ~ 1.3MJ

~60-70%



$P_{ablation}$ ~ 100 Mbar

E_{laser} ~ 1.8MJ

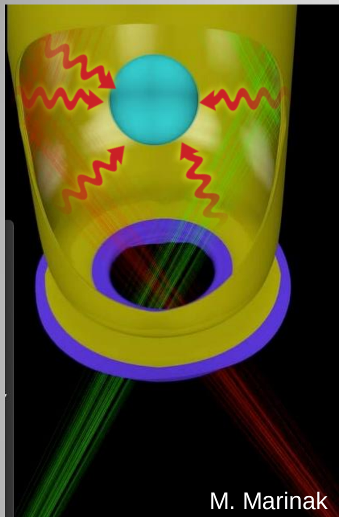
$E_{X\text{-}ray}$ ~ 1.3MJ

~60-70%

E_{abs} ~ 150 kJ

~10%

$P_{ablation}$ ~ 100 Mbar



E_{laser} ~ 1.8MJ
$E_{X\text{-}ray}$ ~ 1.3MJ

~60-70%

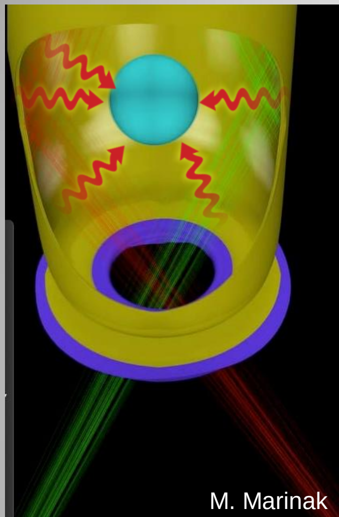
E_{abs} ~ 150 kJ

~10%

KE_{fuel} ~ 15 kJ
Speed ~ 370 km/s

~1%

$P_{ablation}$ ~ 100 Mbar

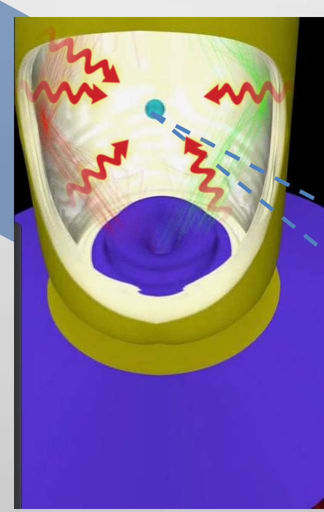


E_{laser} ~ 1.8MJ
$E_{X\text{-}ray}$ ~ 1.3MJ

~60-70%

E_{abs} ~ 150 kJ

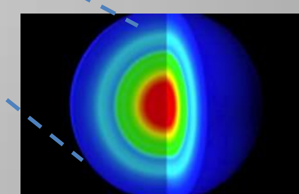
~10%



KE_{fuel} ~ 15 kJ
Speed ~ 370 km/s

~1%

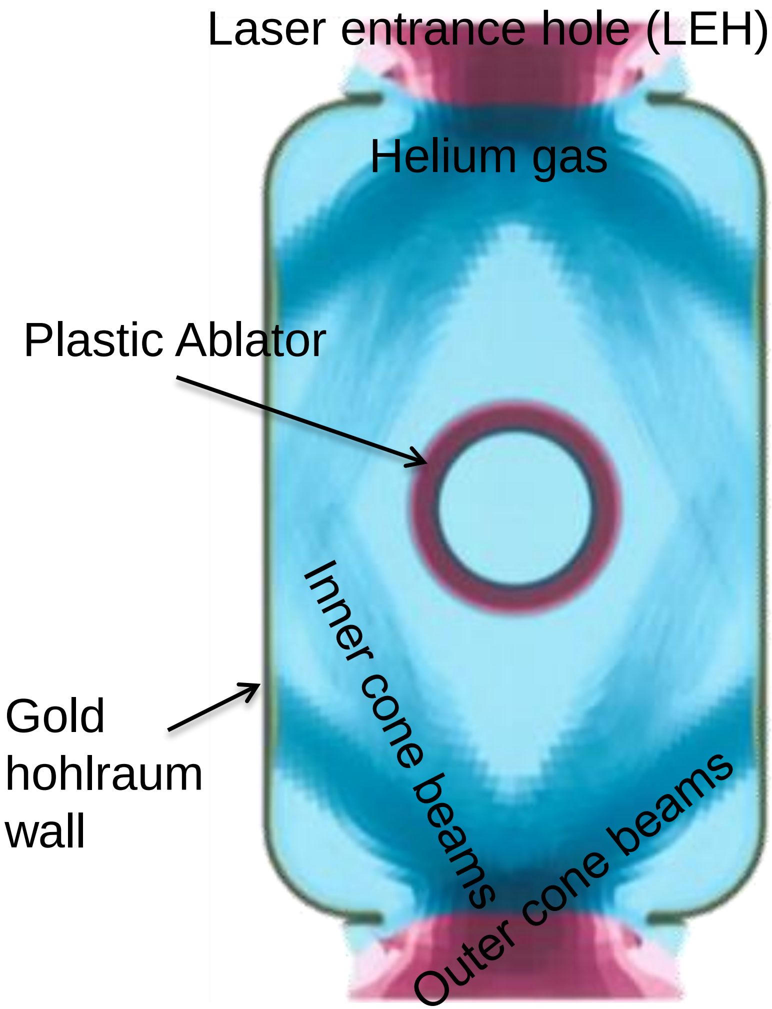
P_{stag} ~ 300,000 Mbar



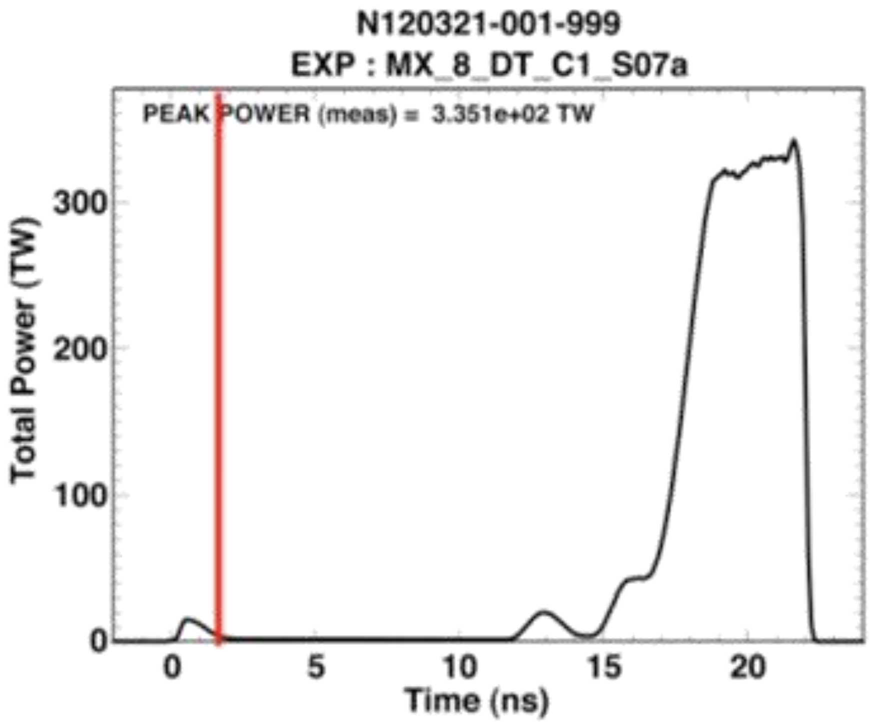
PdV_{HS} ~ 5 kJ

~1/4%

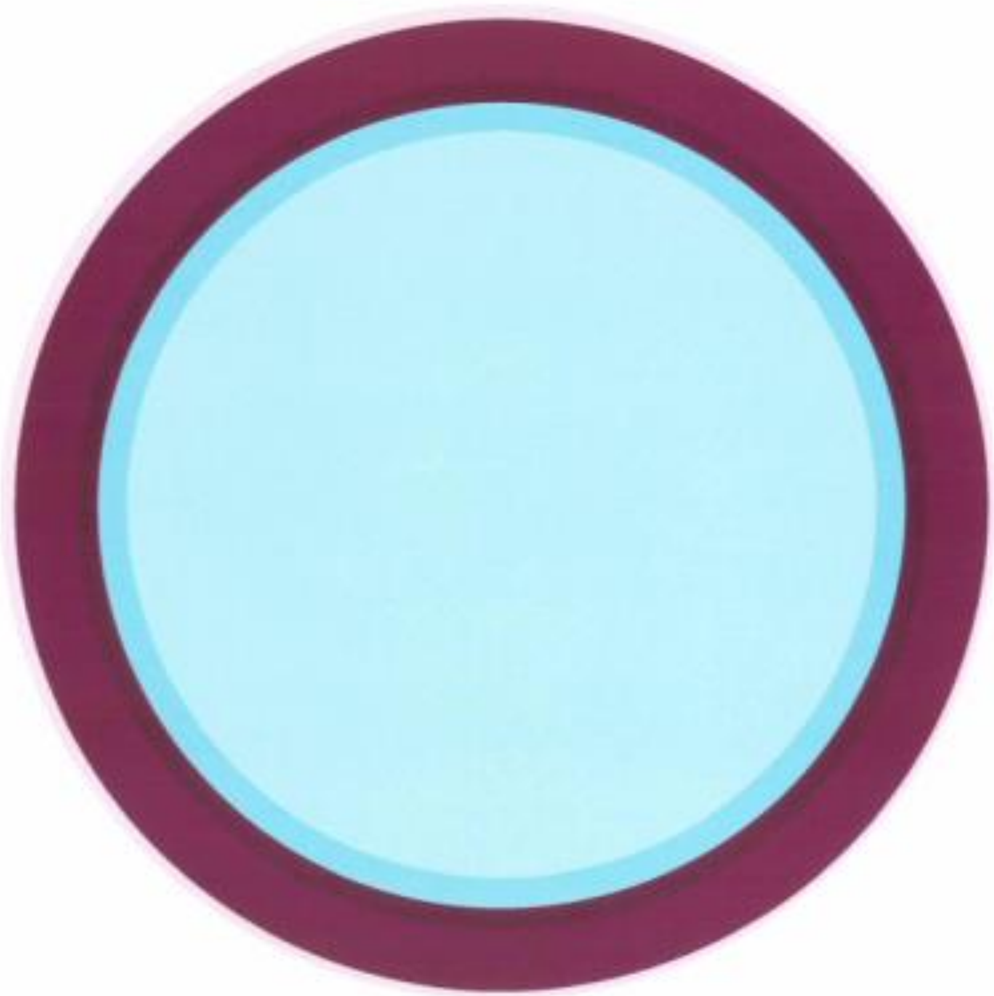
The hohlraum must provide a symmetric implosion with the required velocity and fuel adiabat



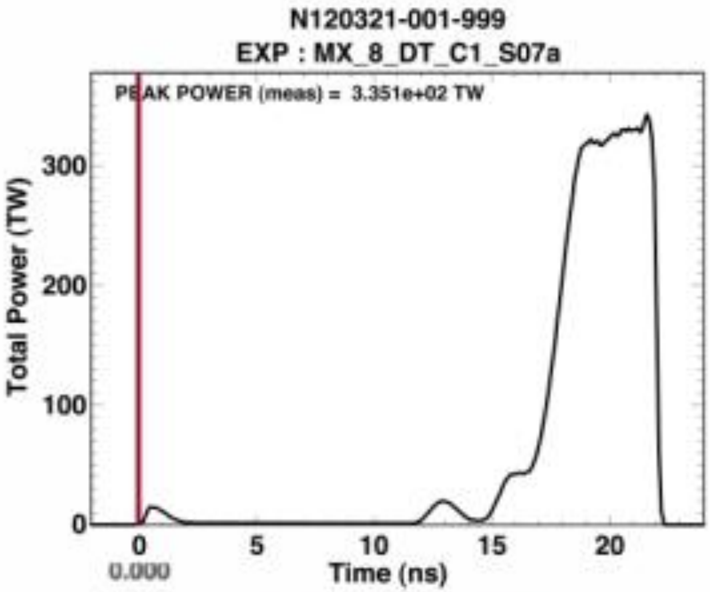
Laser "Pulse-shape"



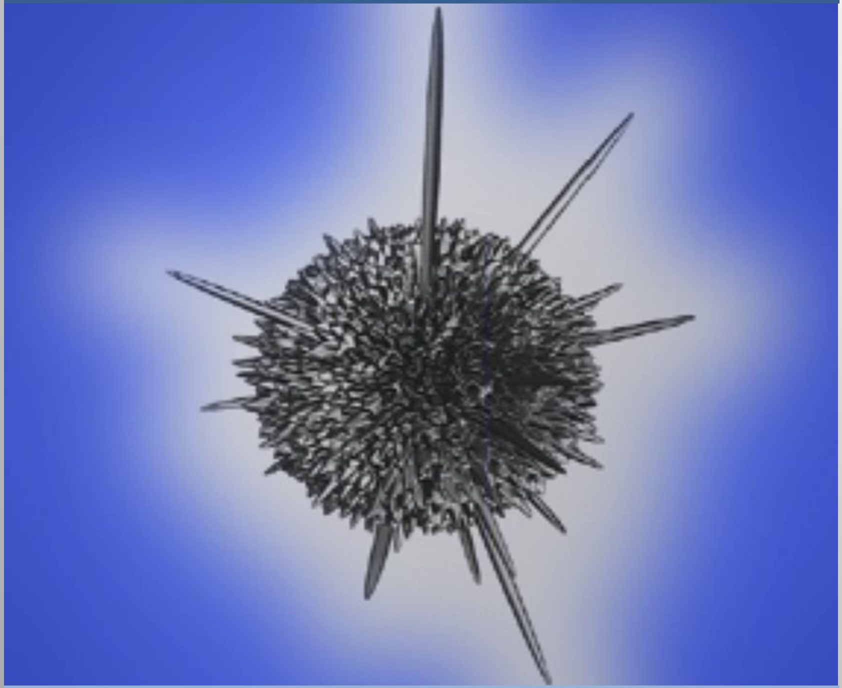
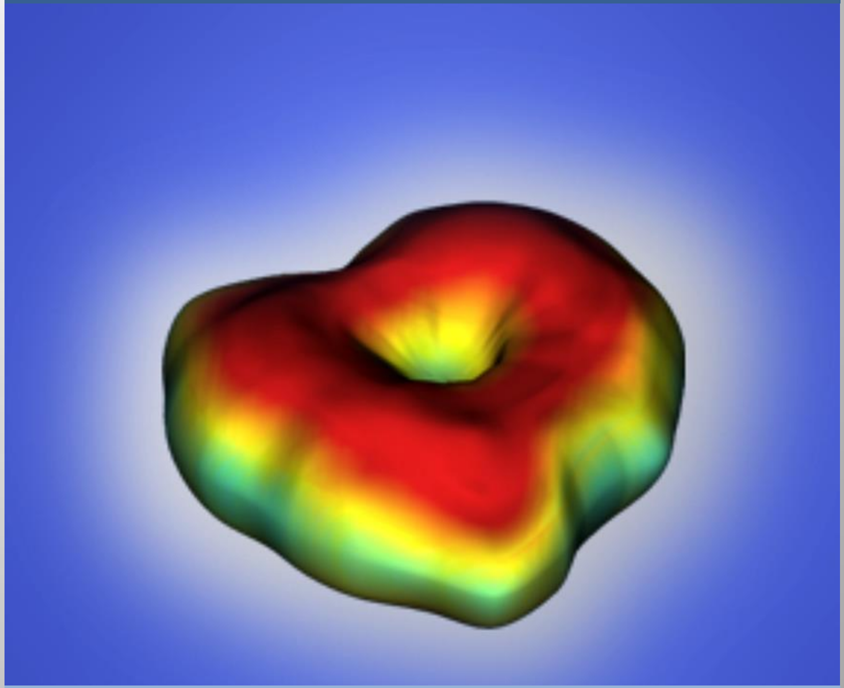
The capsule must be designed to withstand hydrodynamic instabilities



VGLayoutHoSm.mov



Major challenges

Capsule instability	Asymmetric DT hot spot
	
Growth x Surface seeds is too large leading to mix at lower velocity than predicted	X-ray push on the capsule is not symmetric enough resulting in loss of efficiency at stagnation

Principal change: high foot implosions are more stable