IFE Chamber Development - To ETF and Beyond

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Presentation to

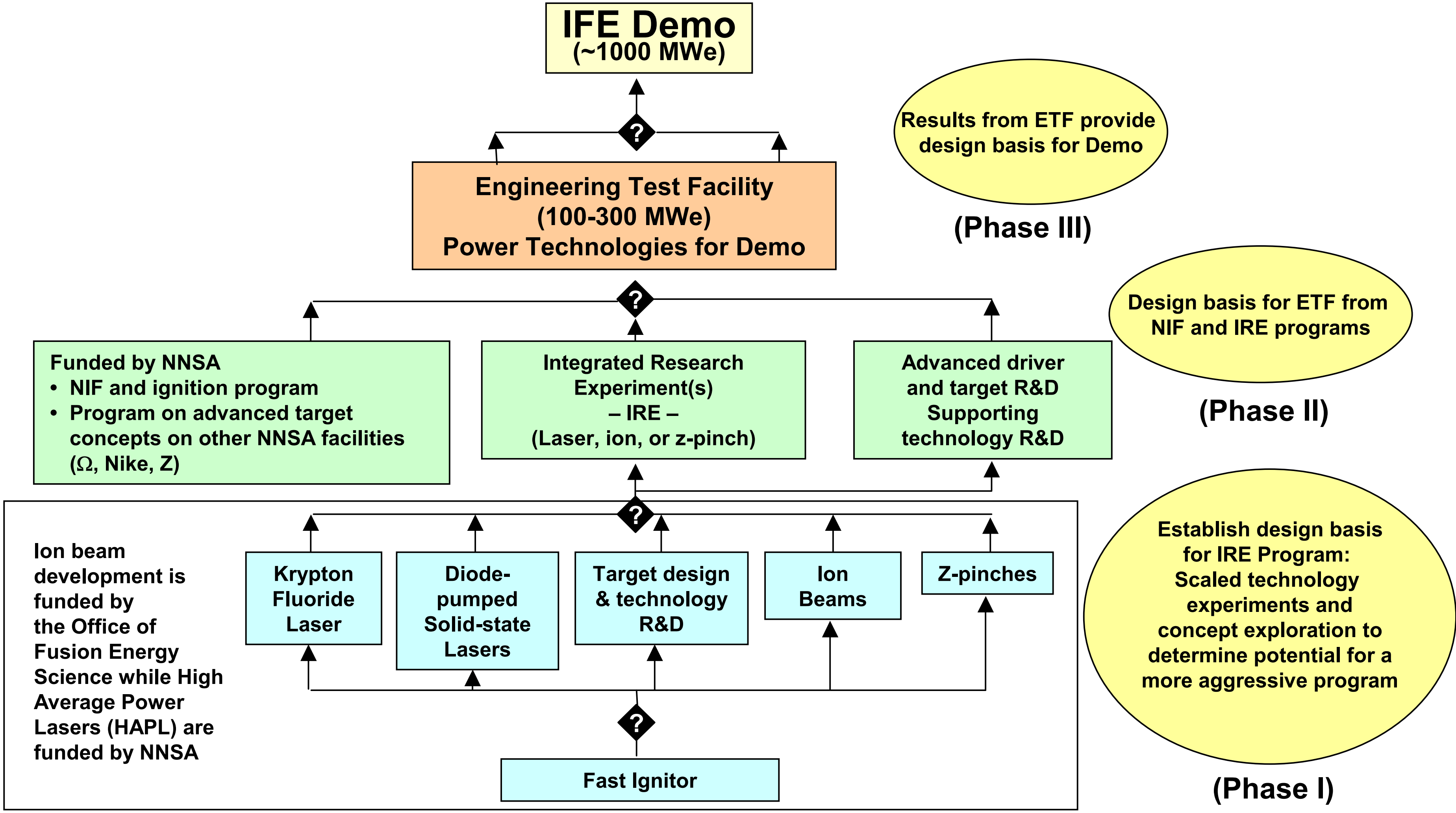
FESAC Development Path Panel

Oct. 28, 2002

Outline

- Multi-phase ETF
- General IFE development path considerations
- IFE Chamber development
  - Thick liquid wall chambers (mainline for HI and Z)
  - Dry wall chambers (mainline for lasers)
- Summary/Conclusions

The IFE Development Path proceeds in 3 phases to an ETF that would be capable of putting electricity on the grid



IFE Demo
(~1000 MWe)

Results from ETF provide design basis for Demo

(Phase III)

?

Engineering Test Facility
(100-300 MWe)
Power Technologies for Demo

Design basis for ETF from NIF and IRE programs

(Phase II)

?

Funded by NNSA
- **NIF and ignition program**
- **Program on advanced target concepts on other NNSA facilities (Ω, Nike, Z)**

Integrated Research Experiment(s)
– IRE –
(Laser, ion, or z-pinch)

Advanced driver and target R&D Supporting technology R&D

?

Ion beam development is funded by the Office of Fusion Energy Science while High Average Power Lasers (HAPL) are funded by NNSA

Krypton Fluoride Laser

Diode-pumped Solid-state Lasers

Target design & technology R&D

Ion Beams

Z-pinches

?

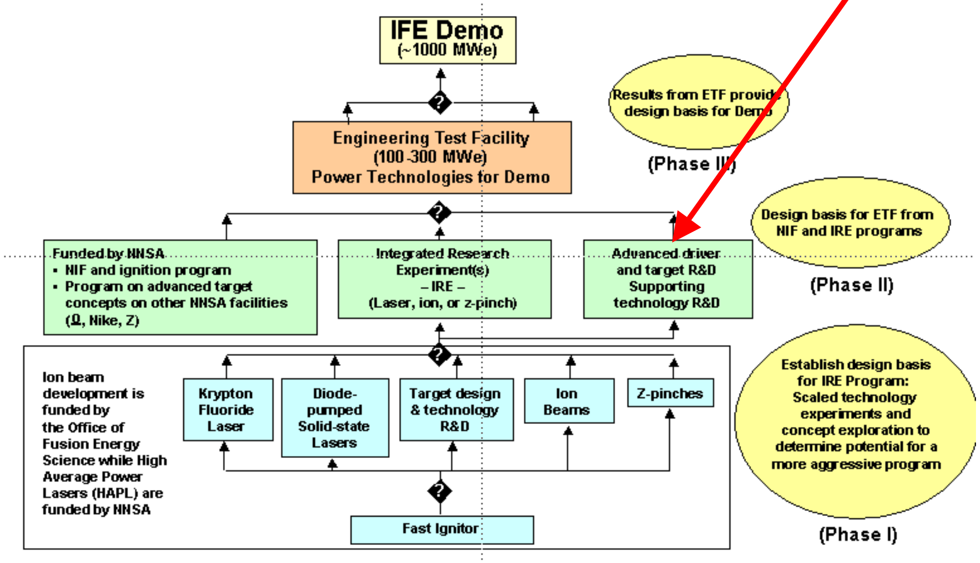
Fast Ignitor

Establish design basis for IRE Program: Scaled technology experiments and concept exploration to determine potential for a more aggressive program

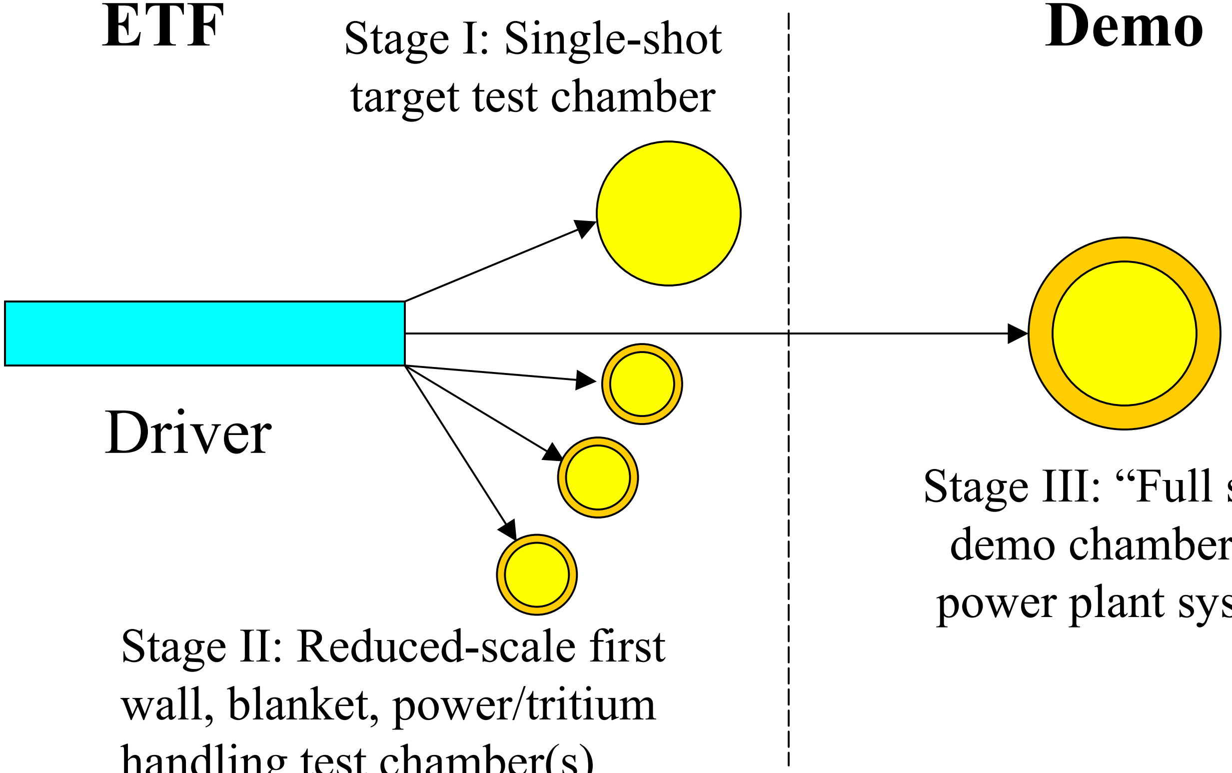
(Phase I)

Chamber development continues in parallel with the IRE programs

Supporting Technology R&D includes chamber material and component development and chamber phenomena testing (e.g., molten salt flow loops, x-ray exposure testing, etc.)



IFE ETF/Demo strategy uses a single driver for many stages



ETF

Stage I: Single-shot target test chamber

Demo

Driver

Stage III: “Full scale” demo chamber and power plant systems

Stage II: Reduced-scale first wall, blanket, power/tritium handling test chamber(s)

- The ETF will perform many functions in IFE development. One of these is expected to be the prime vehicle IFE material and component testing.
- Driver is then used for Demo.

Objectives of the ETF – a strawman

- **System Integration** – Integrate all the major subsystems required for an inertial fusion power plant (driver, targets, fusion chamber, and heat removal system)
- **Target Gain and Yield** – Demonstrate target gain high enough for attractive economics; study target physics to maximize yield in single shot tests
- **Driver** – Demonstrate driver technology with efficiency and reliability needed for economical power, including beam steering and propagation through post shot chamber conditions
- **Chamber & Nuclear Technology** – Operate at rep-rate with reduced yield (and thus power) to investigate chamber dynamics; demonstrate recovery between shots; radiation damage testing*
- **Target Fabrication and Injection** – Demonstrate high rep-rate production (scalable to low cost), target injection and tracking
- **Heat Transfer and Other Plant Systems** – Demonstrate HTS, power conversion, electricity production, and safe operation including recovery of tritium
- **Reliability Testing** – gaining data, experience on reliability, O&M in integrated system

*W. R. Meier, D.A. Callahan Miller, J.F Latkowski, B. G. Logan, J. D Lindl, P.F. Peterson, "An Engineering Test Facility of Heavy Ion Fusion – Options and Scaling ," *Fusion Tech*., **39**, 2, 671-677 (2001).

Phased ETF experiments study IFE technology with increasing levels of integration

- **High rep-rate driver operation with required efficiency**
- **Single shot, high gain target experiments to optimize target designs**
- **Short duration (minutes), burst mode tests at low yield to prove and optimize chamber designs**
  - tritium breeding not required
  - batch production of targets
  - demonstrate consistency of target performance and chamber clearing
- **Steady state, average power tests for days/weeks/months**
  - automated target production
  - include tritium breeding and recovery
  - include heat removal and power conversion
  - demonstrate electricity production
- **Upgrade chamber and power plant components to demo scale**

A starting thesis: IFE should take advantage of its unique characteristics in planning the development path to fusion power

- Separability of driver, chamber, targets
- Point source of neutrons
- Ability to control power by varying rep-rate and yield
- Use of fluids (gases and liquids) to reduce radiation damage (x-rays, ions, neutrons)

Separability

- High value components are non-nuclear, no remote handling/maintenance
- Phase-I (current, near-term)
  - Develop and test components at scale appropriate to that component prior to integration (e.g., sub-scale driver beam line, small-scale chamber tests, bench-scale demonstration of target fab techniques, etc.)
- IRE
  - Integration at scale appropriate for particular driver/chamber/target combination sufficient for determining cost and performance of ETF
- ETF
  - Multi-phase approach taking advantage of driver investment (single shot at high yield, burst mode, high rep-rate tests at low yield, materials development, potential net power production at small scale)
- Demo
  - Utilize ETF driver investment
  - At scale with clear extrapolation to commercial plant

Point source of fusion energy release allows multi-phase ETF by changing structures surrounding target position

- Chamber configuration does not directly impact fusion ignition/burn
  - Has allowed innovative first wall/blanket concepts/configurations
  - Encouraged designing around problems (e.g., liquid walls, segregated function first walls, etc.)
- High neutron wall loading can be achieved at low fusion power for first wall and blanket material tests
- Open solid angle fraction for beam delivery is unchanged as system is scaled to low power ETF
  - allows large blanket coverage fraction for testing
  - permits self-sufficient tritium breeding at ETF stage

Rep-rate and target yield – knobs for flexible development

- ETF
  - Most likely build full scale (multi-MJ) driver
  - Single shot (or burst mode) high yield chamber to do target physics in early phase (development of targets requires minimal T consumption)
  - Separate chamber or chamber insert (mini-chamber) operated at lower yield,[1] high rep-rate (appropriately scaled based on chamber type)
    - Chamber dynamics and first wall testing (could be burst mode)
    - Longer-term average power tests
    - Tritium breeding and recovery
    - Heat removal, power conversion, net electric power production[2]

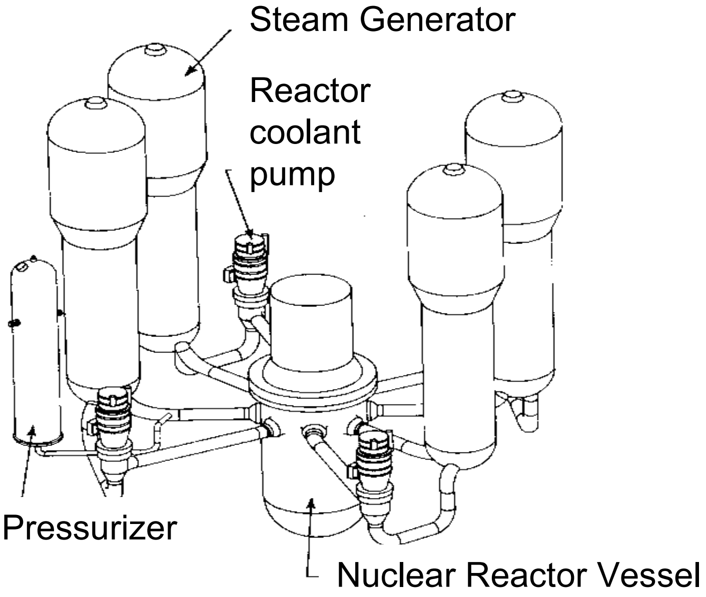
Notes –

[1] Z ETF would operate at 500 MJ and 0.14 Hz = 70 MW, full plant is multi-chamber

[2] To keep power/tritium handling cost low, the ETF is operated at low yield and likely lower target gain. Thus, the driver recirculating power fraction could be high for this phase. Proof of high yield, high gain targets in the single shot or burst mode tests provides basis for projected performance of demo plant.

Heat transfer components can be tested at near ½ scale

- Power plants typically have 2-4 heat transfer loops
- Assuming a 2500 MWt four loop design gives 625 MWt each
- ETF can test a single loop at 335 MWt or ~ ½ commercial scale
- Full length heat exchanger with fewer tubes will be used to preserve heat transfer effects.



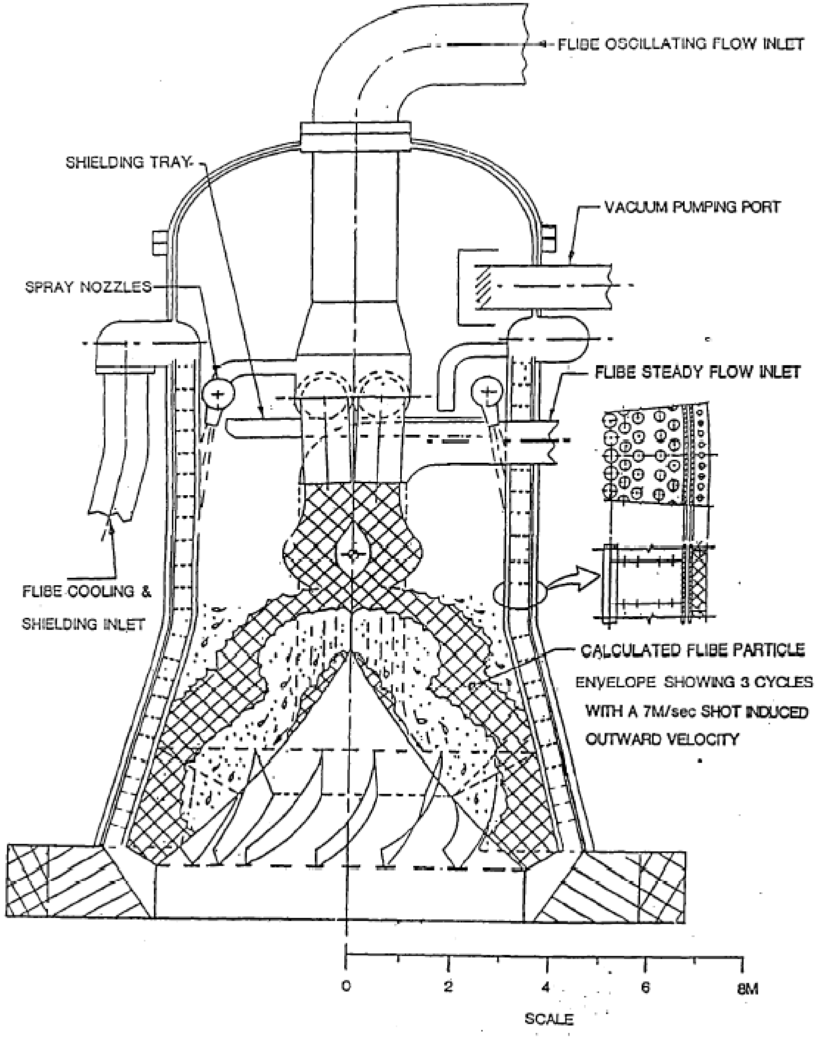
Westinghouse 4-loop reactor coolant system

W.J. Hogan and W.R. Meier, “A Lower-Cost Development Path for Heavy Ion Fusion,” *Il Nuovo Cimento*, **106**, 12, 1971-1982 (1993).

Introduction to IFE chamber concepts

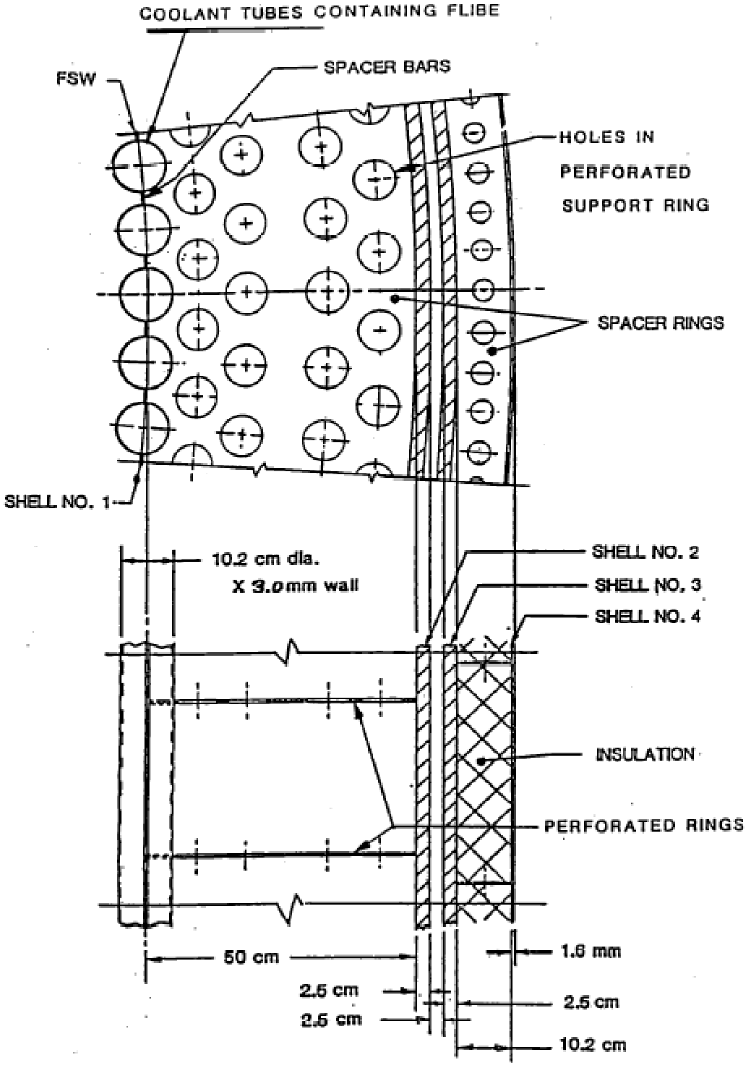
- Thick-liquid wall (TLW) chambers
- Dry-wall chambers
- Wetted-wall chambers

Thick liquid walls allow major chamber structures to last many years



- An array of molten salt jets protect steel structures from direct exposure to x-ray, target ion/debris and neutrons.
- Effective shielding thickness is 50 cm or more.
- Neutron energy deposition in FW is < 2 W/cm^3 even though chamber is very compact (R_{fw} = 3.2 m)
- First wall is a flow guiding structure, swelling tolerant
- Vacuum vessel is shielded by additional 50-cm-thick molten salt region

Avoiding need for vacuum integrity eases qualification for flow guiding structures



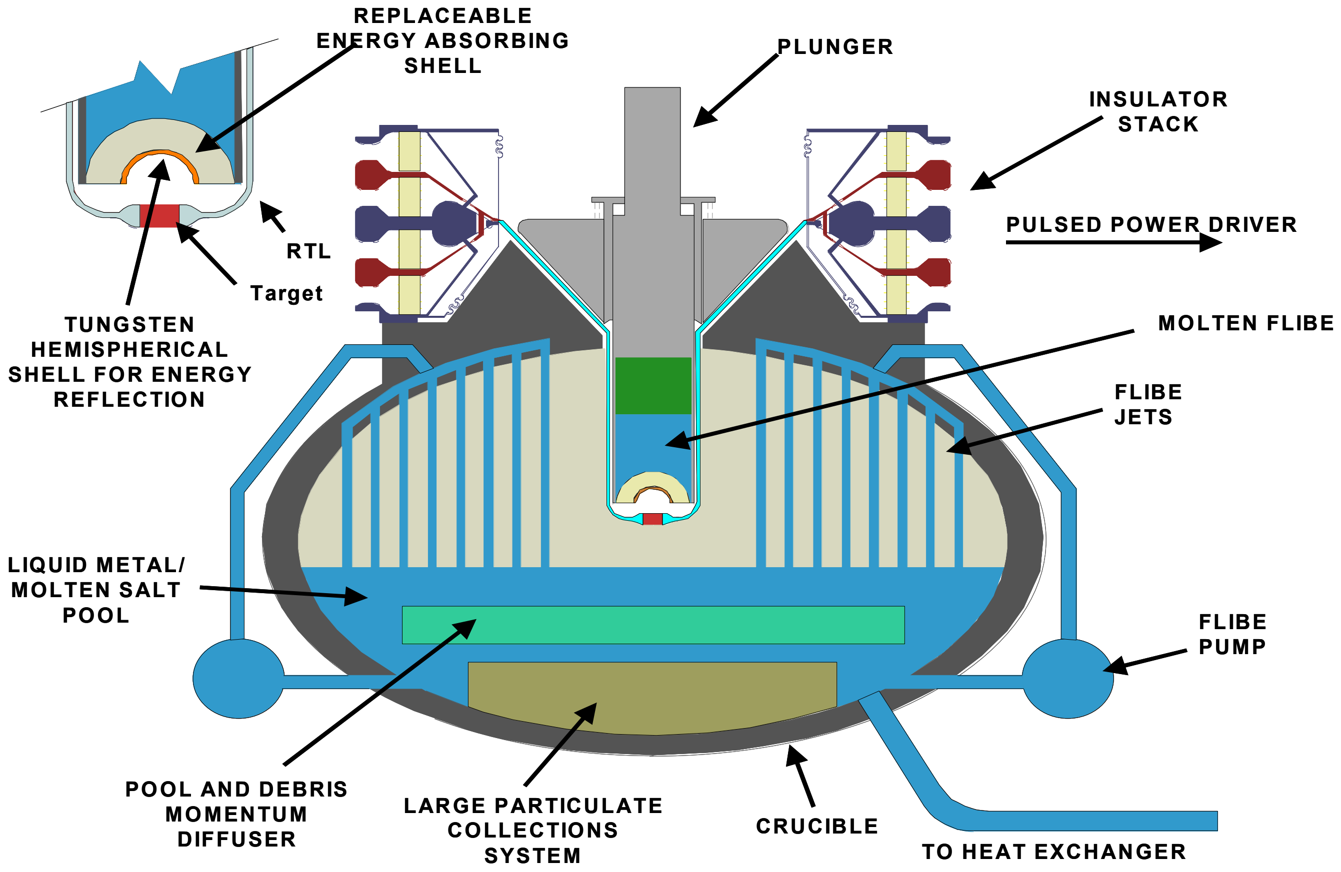
- Uses thin coolant tubes as FW
- Horizontal, perforated plates guide flow and provide structural support to FW
- VV wall is multi-layered to stay within thermal stress limits

First wall failure is not a safety issue.

Alternative, flexible, porous designs are possible.

Replacement, if required, would not have significant economic impact.

Z-Pinch IFE power plant would use thick liquid walls



Non-nuclear development program prior to ETF gives high confidence in ETF

- Current: university experiments on liquid jets, condensation, modeling of fluid dynamics, vapor flow, etc.
- Next steps: Flow loop(s)
  - With water (larger scale)
    - Multiple jet interactions
    - Pocket disruption by chemical detonation, regeneration
  - With molten salt to test
    - Full-scale single jets
    - High velocity injection, nozzles
    - Chemistry and material recovery (e.g., target debris)
    - Cyclic thermal and mechanical loading
- ETF: neutron effects tests possible
  - Liquid response to isochoric heating
  - Tritium breeding
  - Neutron damage testing

A preliminary ETF study was completed for HIF

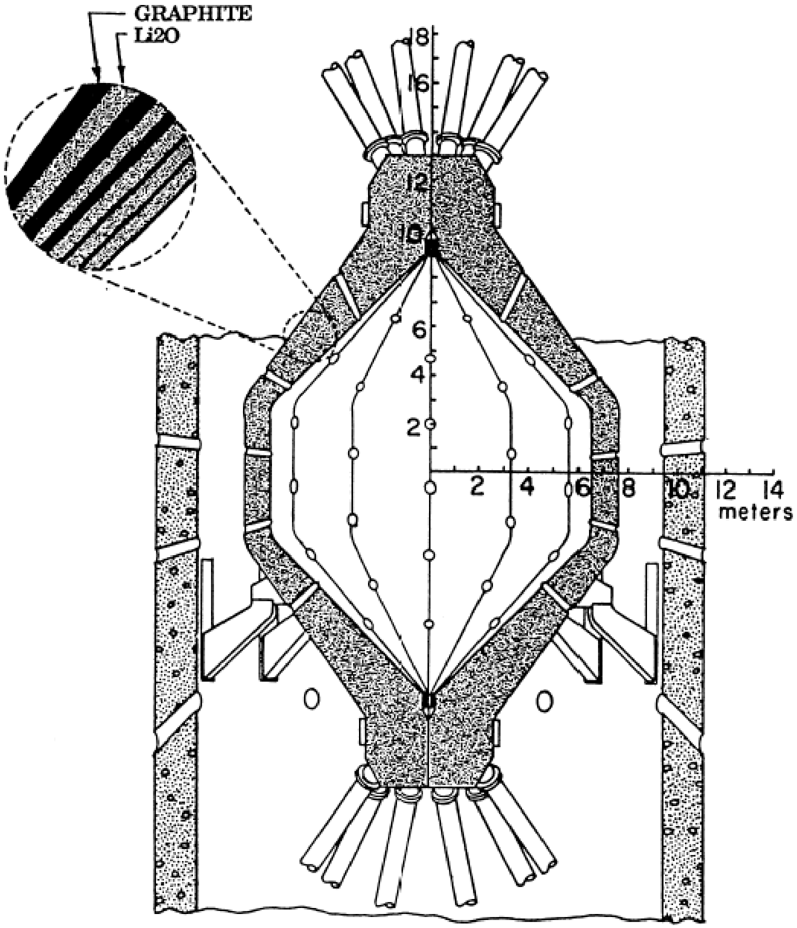
- An Engineering Test Facility of Heavy Ion Fusion – Options and Scaling / W. R. Meier, D.A. Callahan Miller, J.F Latkowski, B. G. Logan, J. D Lindl, P.F. Peterson, *Fusion Tech*., **39**, 2, 671-677 (2001).
- Mapped out design space and scaling considerations for heavy ion driver with thick liquid wall chamber
- General philosophy applies to laser and Z-driven IFE
- Preliminary assessment indicates favorable scaling for gas-protected, dry-wall chambers, but more work is needed

HI ETF achieves prototypic or accelerated blanket testing at greatly reduced chamber cost

	ETF	**Power Plant**
Yield, MJ	30	350*
Rep-rate, Hz	9.5	6.0*
Fusion power, MW	285	2100
Thermal power, MWt	335	2480
Capacity factor, %	50	80
1st wall radius, m	1.2	3.0
Chamber mass, tons	~33	208
1st wall annual fast n° fluence (> 0.1 MeV), n/cm^2-y	1.3×10^{22}	1.6×10^{21}
1st wall heating, W/cm^3	166	37
TBR (pocket/total)	0.55/1.23	1.18/1.26
Magnet fast n° fluence (> 0.1 MeV) to coils, n/cm^2-y	1.5×10^{18}	4.1×10^{17}
Magnet annual dose, MGy/y	64	1.5
Estimated magnet lifetime, y	1.6-6.7	24-66

*Z-IFE power plant = 3000 MJ @ 0.1Hz, ETF = 500 MJ @ 0.14 Hz

Sombrero is an example of a dry-wall concept



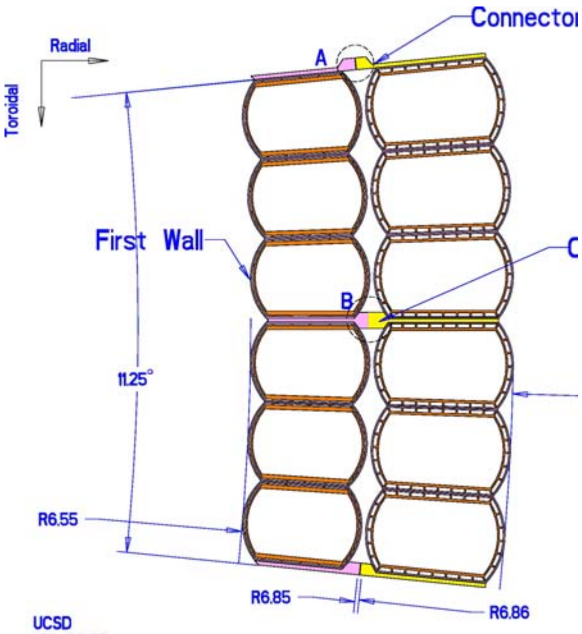
- Uses gas protection, W-armor coating, or engineered surface (e.g., brush-like) to protect first wall structure from x-ray and target ions/debris
- ~30% of fusion power must be conducted through solid FW
- FW/blanket coolant is flowing solid breeder ($Li_2$0) with low pressure He gas to assist in T purge and flow control
- Design could tolerate some degree of micro-vacuum leaks
- First wall configurations under consideration are:
  - C/C composites (original design)
  - C/SiC (Sirius)
  - W/SiC, W/nanocomposited steels /stainless steel (HAPL, ARIES)

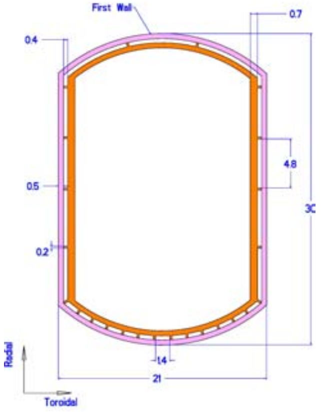
Fig. 3.15. Cross section of SOMBRERO chamber.

Example of Adapting an MFE Blanket Design to IFE

- Variation of ARIES-AT blanket
- High performance blanket with possibility of adjusting wall temperature to satisfy target thermal control requirement
- Simple, low pressure design with SiC_f/SiC structure and Pb-17Li coolant and breeder.
- Innovative design leads to high Pb-17Li outlet temperature (~1100^{o}C) while keeping SiC_f/SiC structure temperature below 1000^{o}C leading to a high thermal efficiency of ~ 55%.
- Plausible manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.
- Modular blanket for ease of replacement.

Blanket & First Wall Segment





UCSD

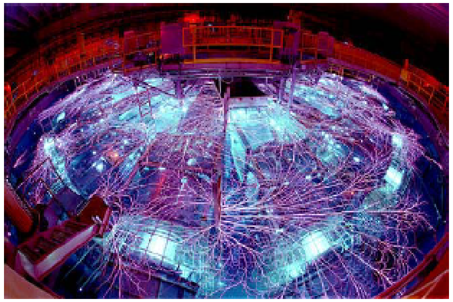
Dry-wall development facilities

- Current:
  - Fundamental material studies, bonding of armor to first wall structure, development of other engineered surfaces (fiber walls, nanostructured materials)
  - Single/multiple effect test of response to threat (small samples tested with various x-ray, ion sources, some for many pulses, some at operating temperature)
  - Ion implantation studies at IFE relevant temperatures
- Next steps:
  - FW endurance tests (could use laser IRE with gas bag targets to produce x-rays, ions)
  - Will also test optics
  - Use mini chamber with IRE driver for chamber tests
  - Development of C/C or SiC structures for testing in ETF
- ETF: Prototypical testing (J/cm^2, rep-rate, temp) including neutron heating/damage effects

Materials evaluation:

We have exposed candidate first wall materials to fusion relevant threats

X-rays-
Z –machine
(Sandia)



Ions-
RHEPP-1
(Sandia)

	Material	Predicted Ablation Threshold	Measured Ablation Threshold	Measured Roughening Threshold	Predicted Threat to wall*	
					154 MJ target	**400 MJ target**
X-rays (10 nsec exposure)	Pyrolitic Graphite	4.0 J/cm^2	3.5 - 4 J/cm^2	2.5 J/cm^2	0.40 J/cm^2	1.20 J/cm^2
	Tungsten	not done yet	2 J/cm^2	1.3 J/cm^2		
IONS (60 nsec exposure)	Pyrolitic Graphite	4.5 J/cm^2	3.5 - 4 J/cm^2	2.5 J/cm^2	8.5 J/cm^2 (1.41 J/cm^2)	21.1 J/cm^2 (3.52 J/cm^2)
	Tungsten (pure)	4.75 J/cm^2	5 J/cm^2	1.25 J/cm^2		
	Tungsten + 25% Re	Not yet modeled	5 J/cm^2	3.5 J/cm^2		

* Wall at 6.5 m, parenthesis are adjusts threat for time, t$^{1/2}$ scaling

1) Both Z and RHEPP are producing near relevant threats.
2) Measured ablation thresholds are close to the code predictions.

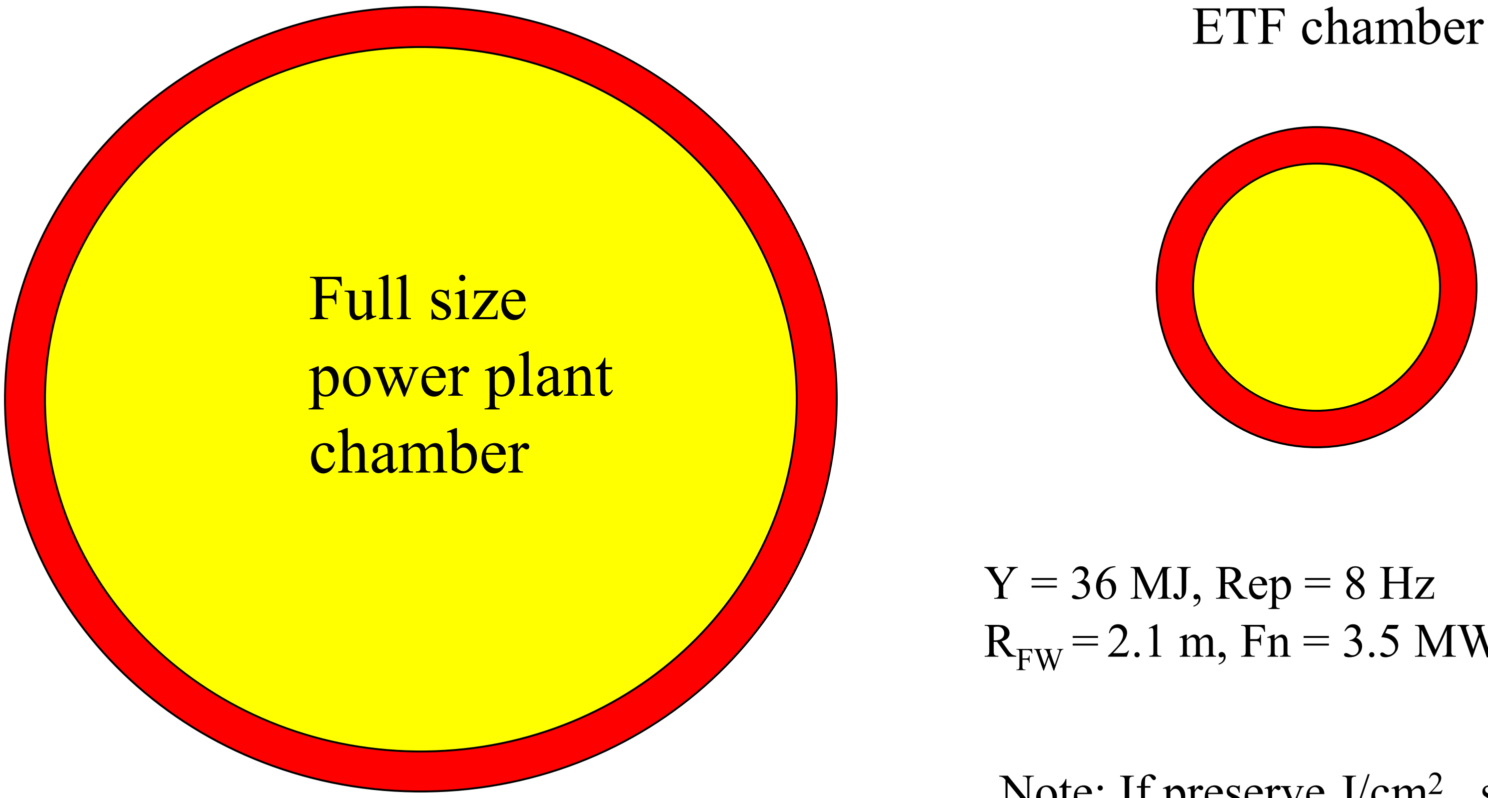
Scaling from IRE to ETF to Demo for laser IFE

	IRE	ETF	Power Plant
Driver Energy, (MJ)	0.1	1-2	2-4
Yield (MJ)	0	50-200 MJ	150-450
Length of runs @ ~5 Hz	1000 burst[b]	Burst /cont	Continuous
Chamber			
Wall radius (m)	3 (or 0.4)[a]	2-5 (or 1.0)[a]	6.5
14 MeV (tot) Neutrons (n/cm^2-shot)	0	3×10^{13}	10^{14} (10^{15})
dpa/year			15=3700 appm He/y
X-rays (J/cm^2)	1.0[b]	0.6-1.0	0.4-1.2
Ions (J/cm^2)	< 1.0	18-28	8-24
Final Optics			
Optics stand-off	10 (0.4)[a]	20 (or 1.0)[a]	30
14 MeV (tot) Neutrons (n/cm^2-shot)	0	2-8$\times10^{11}$	5×10^{12} (10^{13})
Dose			3×10^{9} Gy/y
Gamma-rays	0	0.7-3 Gy/shot	~10^{9} Gy/y
X-rays (J/cm^2)	1.0	14-56	19-76
Ions(J/cm^2)	< 1.0	.3-1.1	0.4-1.1

a. Number in parenthesis assumes mini chamber for accelerated wall materials, optics, and components testing

b. Laser will run for longer periods (approx continuous)

An 1/10th yield ETF test chamber could fit within the full yield chamber



ETF chamber

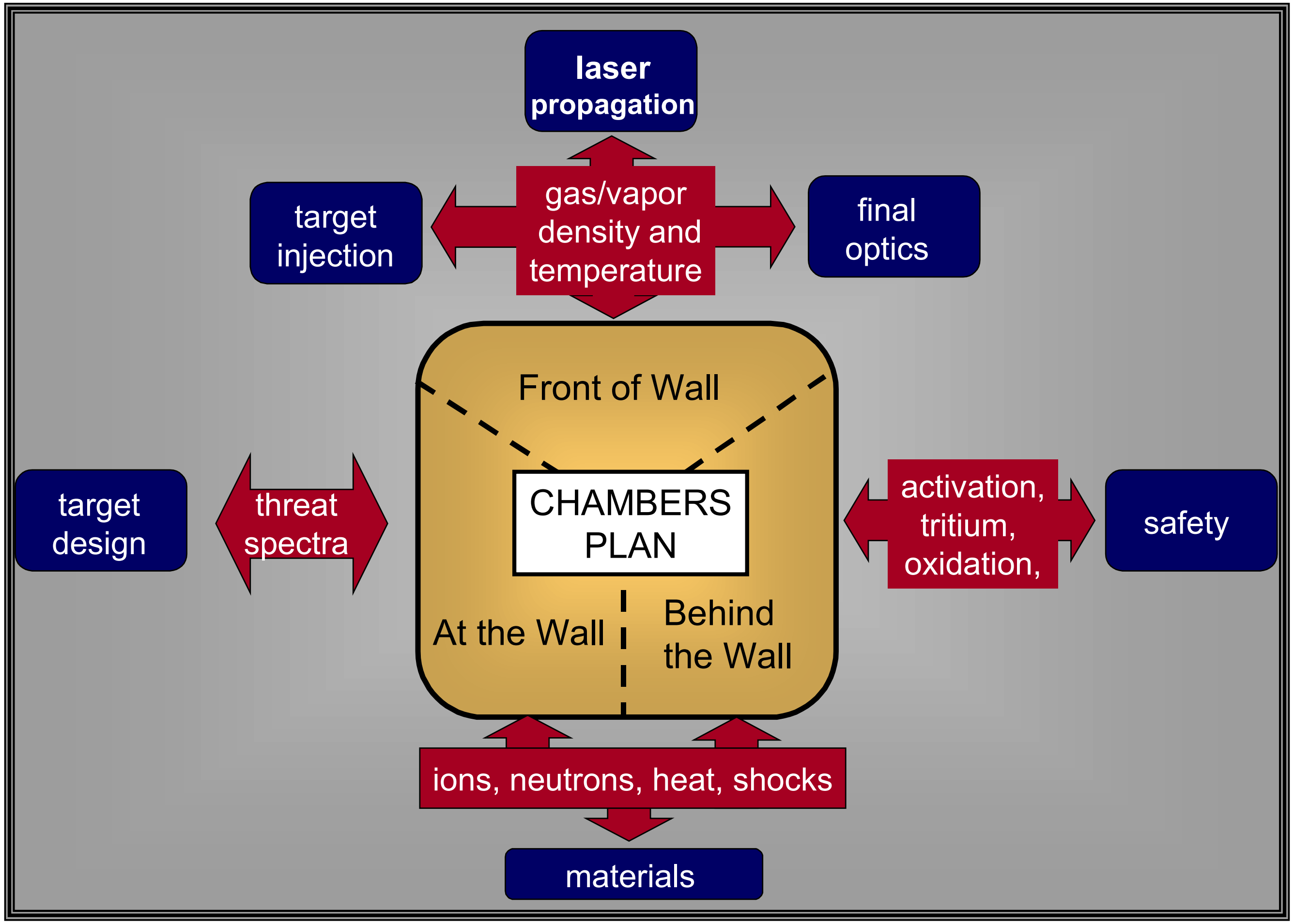
Full size
power plant
chamber

Y = 36 MJ, Rep = 8 Hz
R_{FW} = 2.1 m, Fn = 3.5 MW/m^2

Y = 360 MJ, Rep = 8 Hz
R_{FW} = 6.5 m, F_n = 3.5 MW/m^2

Note: If preserve J/cm^2 , some distortion in neutron volumetric heating (15-25% lower J/cm^3)

Laser IFE program has a chamber development plan



Little work is currently being done on wetted-wall chambers

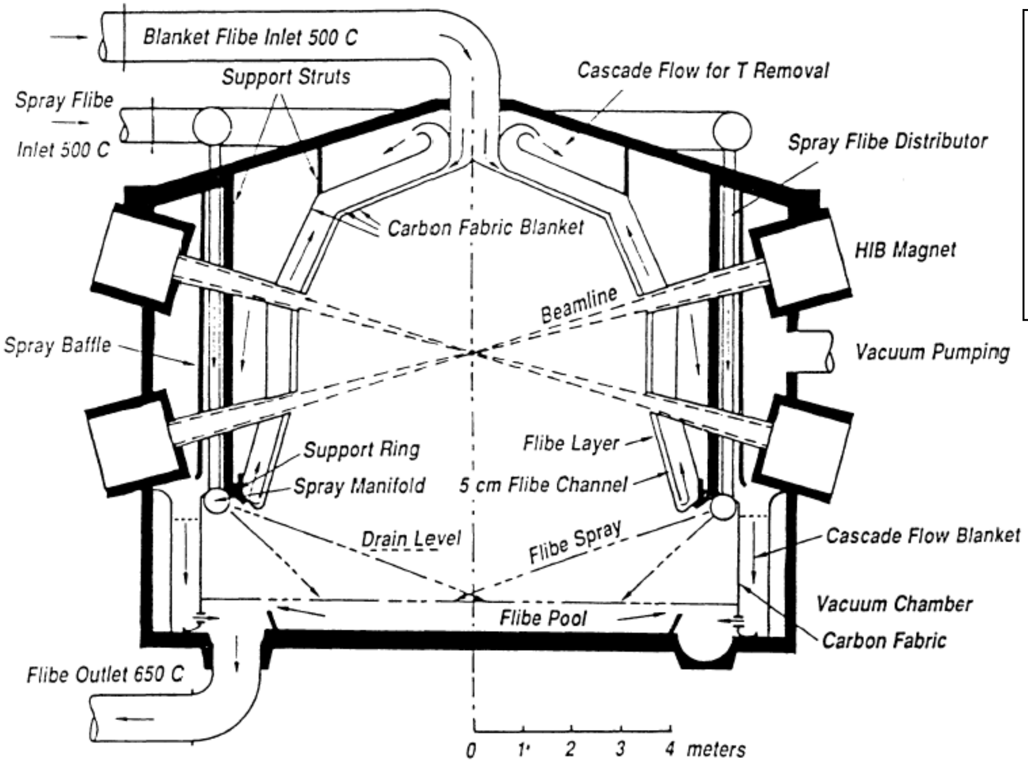


Fig. 2.5. **The final version of Osiris with sprays to ensure vapor condensation. Shown for two-sided illumination using final beam geometry.**

Osiris proposed using flibe breeder/coolant flowing in a porous, flexible carbon fabric FW/blanket structure.

Prometheus used a wetted-wall with an MFE-like breeding blanket

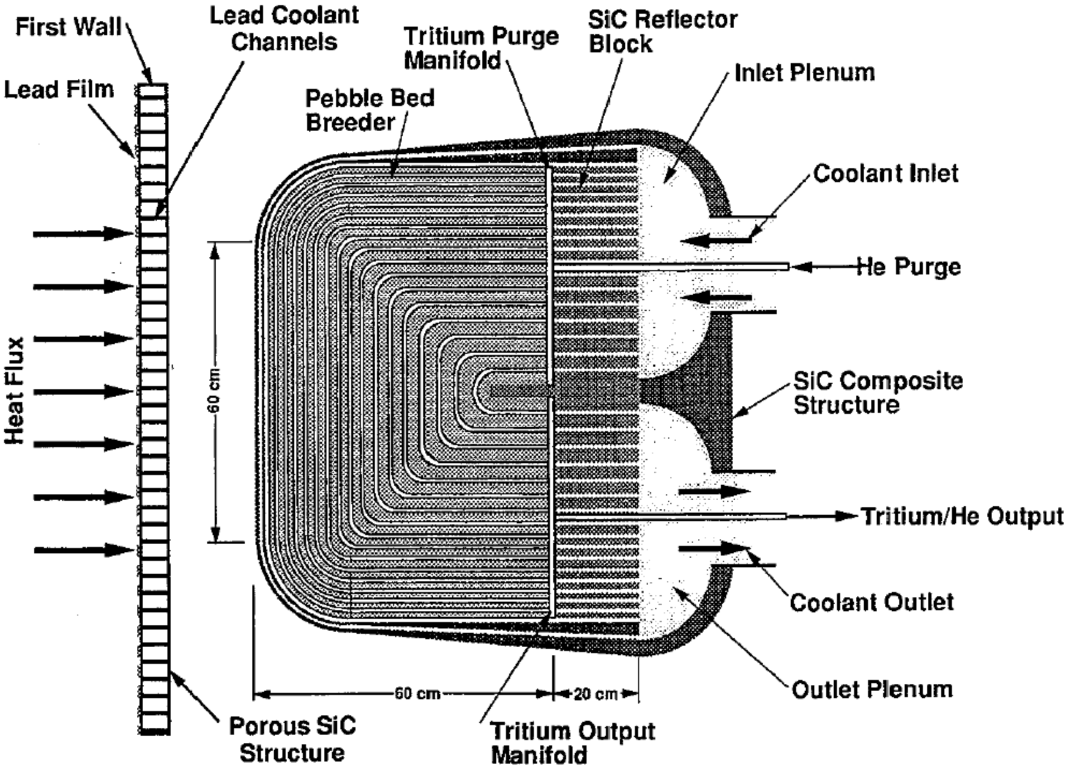


Figure 2.4-9 Schematic of a Blanket Module

Blanket:

- Li_2O breeder
- He cooled
- SiC structures

Vacuum vessel (not shown)

- Ferritic steel

Detail of SiC first wall

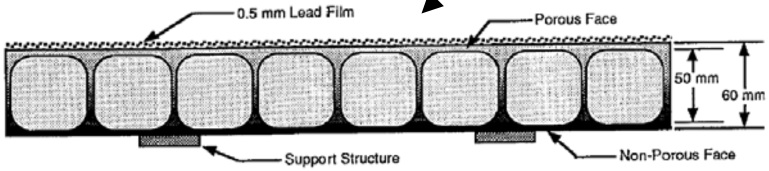
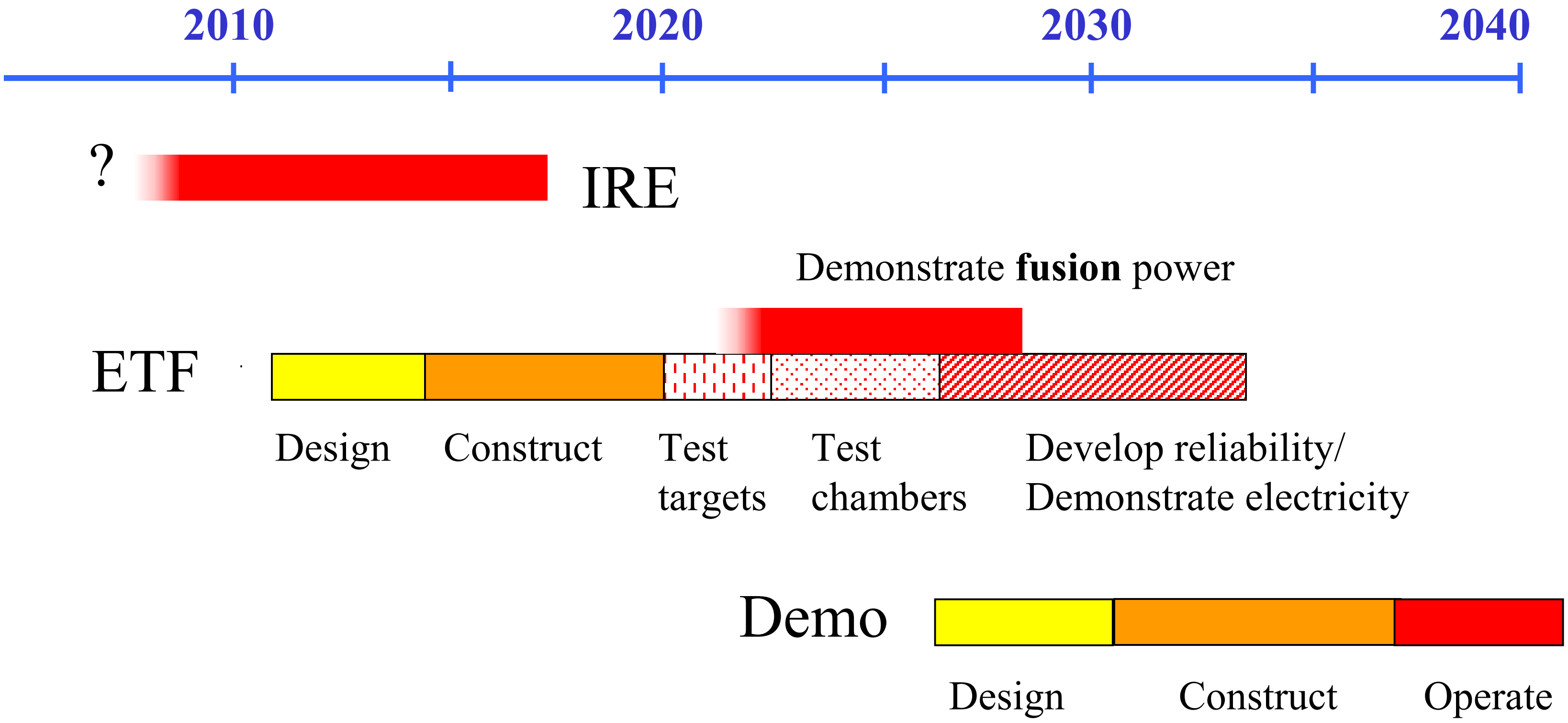
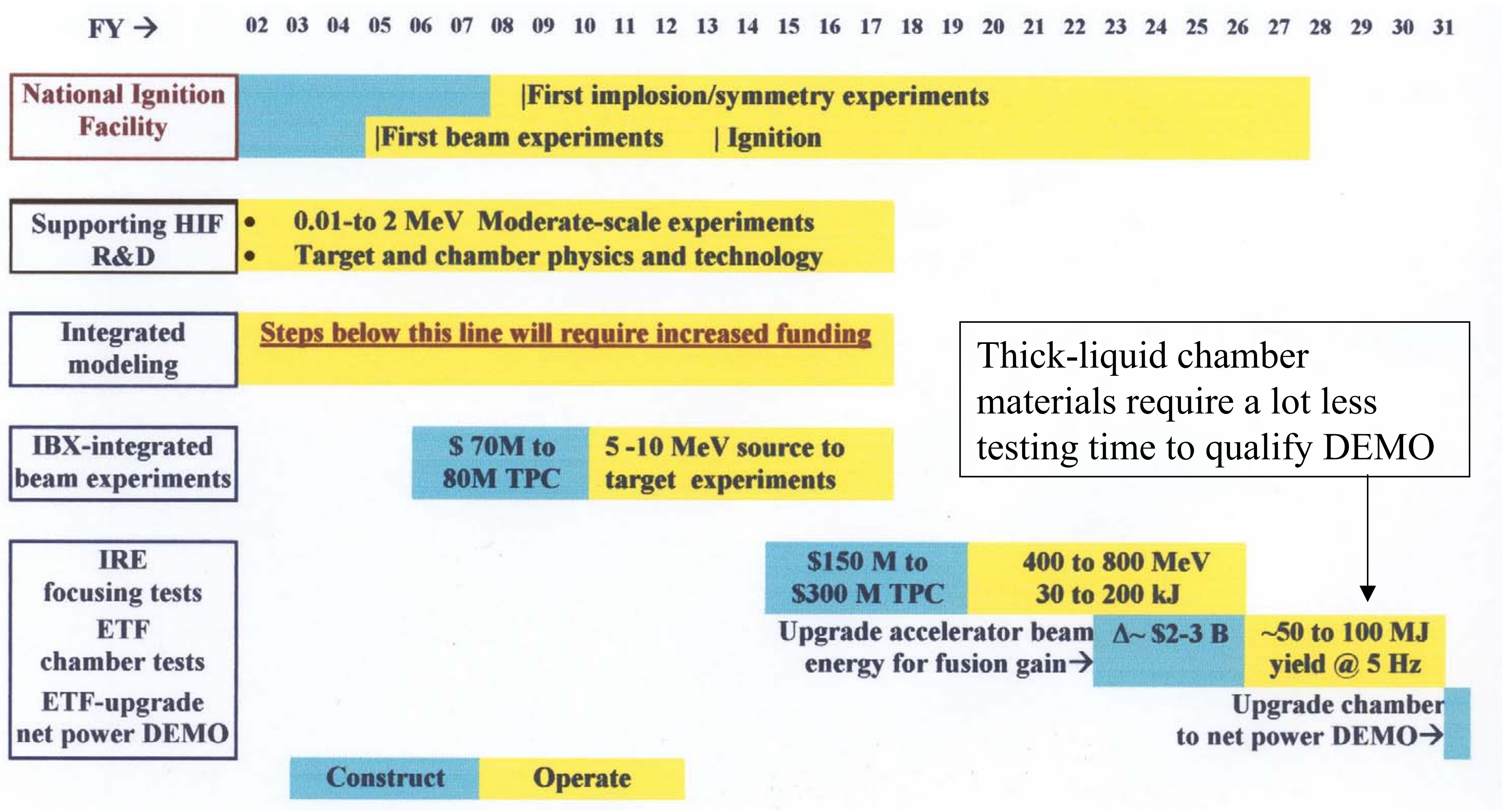


Figure 2.4-8. First Wall Panel; Cross Sectional View

Laser IFE timeline to demo

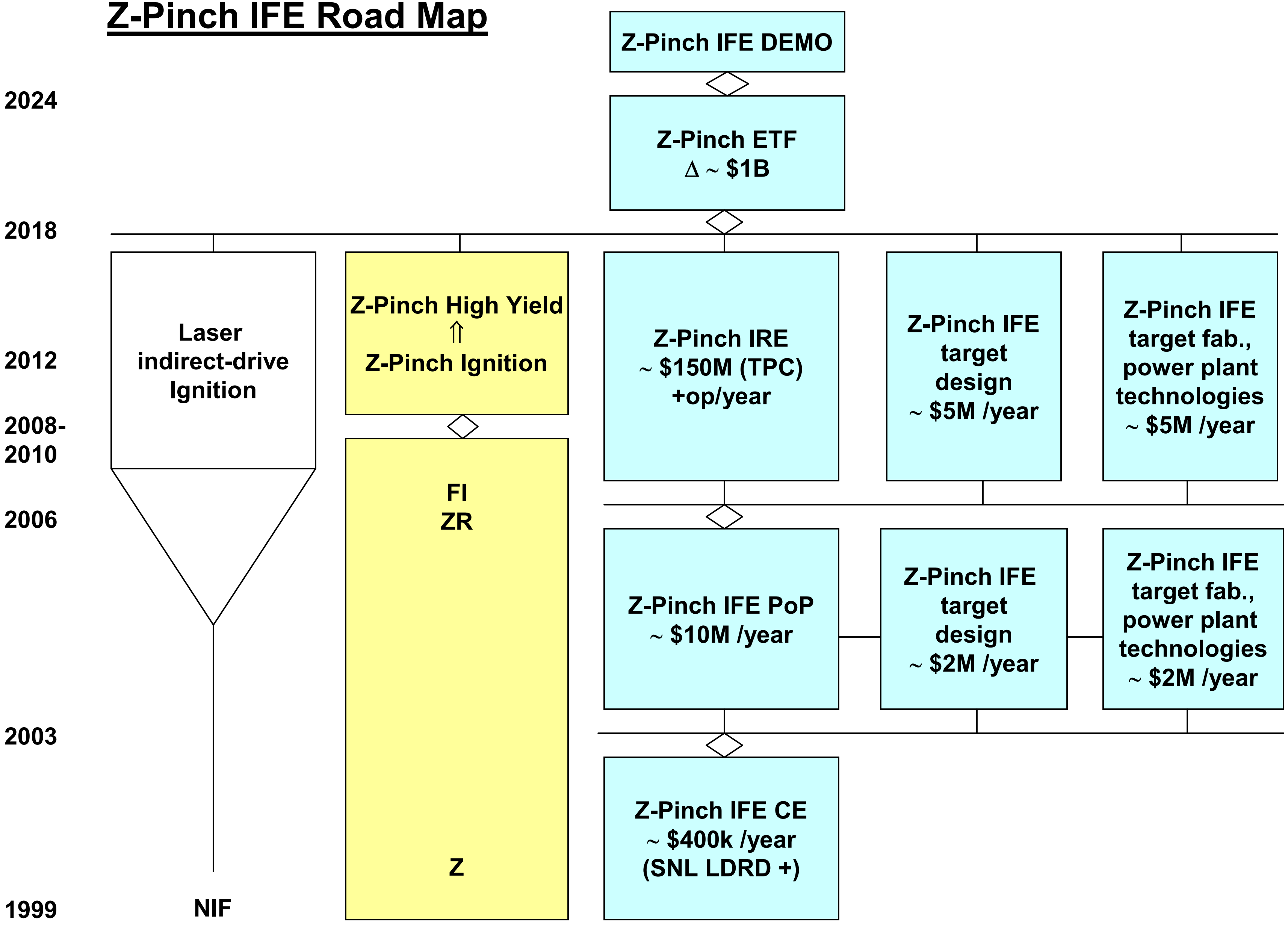


Long range development plan for heavy ion fusion



Thick-liquid chamber materials require a lot less testing time to qualify DEMO

Z-Pinch IFE Road Map



2024

2018

2012

2008-
2010

2006

2003

1999

Z-Pinch IFE DEMO

Z-Pinch ETF
Δ ~ $1B

Laser
indirect-drive
Ignition

NIF

Z-Pinch High Yield
⇑
Z-Pinch Ignition

FI
ZR

Z

Z-Pinch IRE
~ $150M (TPC)
+op/year

Z-Pinch IFE
target
design
~ $5M /year

Z-Pinch IFE
target fab.,
power plant
technologies
~ $5M /year

Z-Pinch IFE PoP
~ $10M /year

Z-Pinch IFE
target
design
~ $2M /year

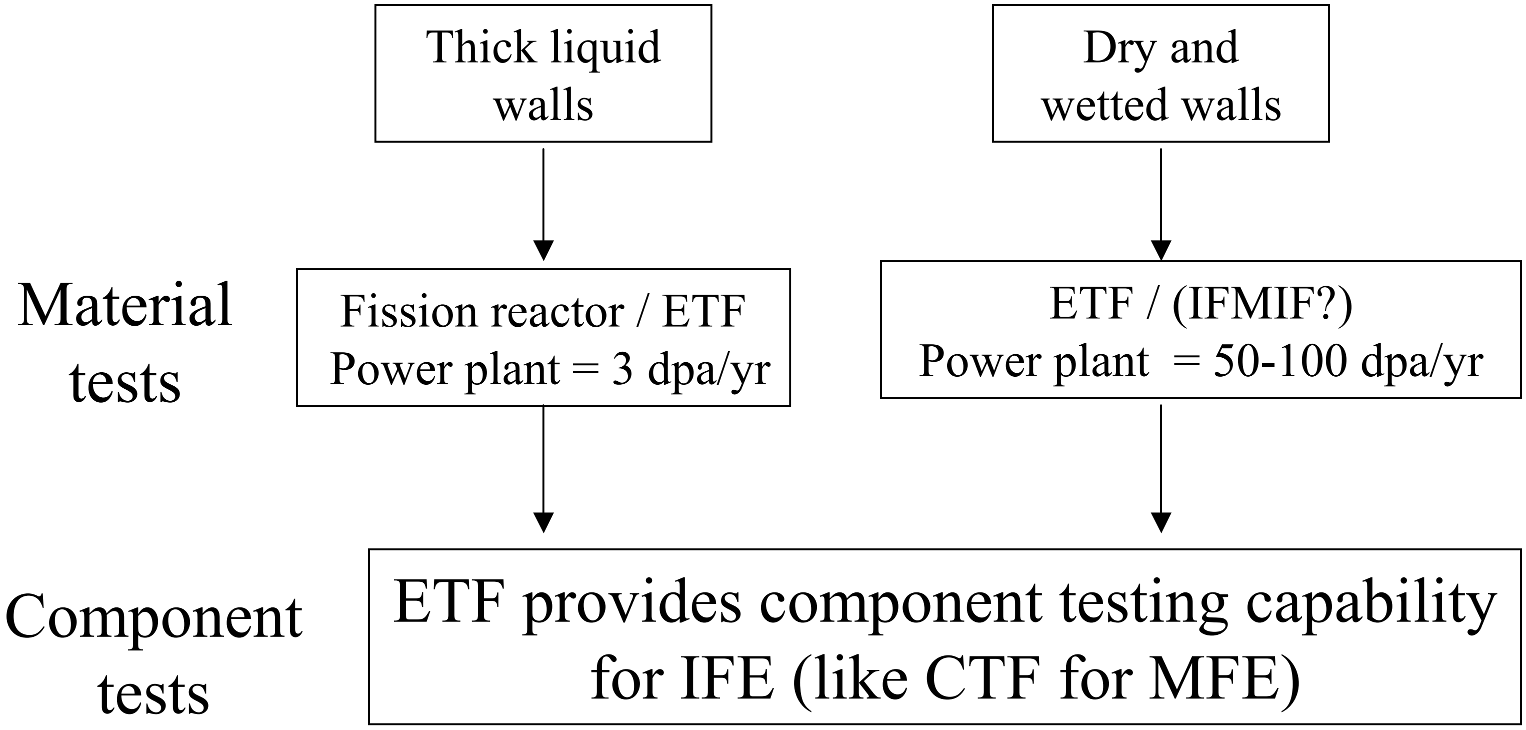
Z-Pinch IFE
target fab.,
power plant
technologies
~ $2M /year

Z-Pinch IFE CE
~ $400k /year
(SNL LDRD +)

Single-shot, NNSA/DP

Rep-Rated for IFE, OFES/VOIFE

Synergistic IFE/MFE materials and component reliability strategies exist



Thick liquid walls

Dry and wetted walls

Material tests

Fission reactor / ETF
Power plant = 3 dpa/yr

ETF / (IFMIF?)
Power plant = 50-100 dpa/yr

Component tests

ETF provides component testing capability for IFE (like CTF for MFE)

Conclusions/Summary

- IFE’s chamber/material development plan takes advantage of separability of driver/chamber/target
- IFE chamber designs often separate key functions (FW, vacuum vessel) and design to mitigate materials issues
- ETF is seen as a multiphase facility that will be capable of
  - Testing high gain/yield targets
  - Radiation damage testing
  - Integrated blanket tests in fusion environment
  - Tritium breeding
  - Producing some net power
- ETF driver could then be used for demo plant, perhaps as a government/commercial venture

Selected Background References

- S.O. Dean et al., “Pilot Plant: An Affordable Step Toward Fusion Power,” *Journal of Fusion Energy*, **11**, 2, 85-97 (1992).
- W.J. Hogan and W.R. Meier, “A Lower-Cost Development Path for Heavy Ion Fusion,” *Il Nuovo Cimento*, **106**, 12, 1971-1982 (1993).
- W.R. Meier, “An Integrated Test Facility for the Development of IFE,” W.J. Schafer Assoc. Report WJSA-94-01 (1994).
- W. R. Meier, D.A. Callahan Miller, J.F Latkowski, B. G. Logan, J. D Lindl, P.F. Peterson, “An Engineering Test Facility of Heavy Ion Fusion – Options and Scaling ,” *Fusion Tech*., **39**, 2, 671-677 (2001).
- F. Najmabadi et al., The Starlite Project Assessment Phase Report,” UC San Diego report UCSD-ENG-005 (1996).
- J. Sethian et al., “A Plan to Develop Dry Wall Chambers for Inertial Fusion Energy with Lasers” Draft report (4/02).
- W.R. Meier et al., “Chamber and target technology development for inertial fusion energy,” Lawrence Livermore National Laboratory, UCRL-ID-133629 (1999).
- R.W. Moir, et al.,"HYLIFE-II: A Molten-Salt Inertial Fusion Energy Power Plant Design - Final Report," *Fusion Technol.,* **25**, 5 (1994).
- W.R. Meier, “Osiris And Sombrero Inertial Fusion Power Plant Designs - Summary, Conclusions, and Recommendations,” *Fusion Engineering and Design*, **25** (1994), 145-157.
- L. Waganer et al., “Inertial Fusion Energy Reactor Studies: Prometheus-L, Prometheus-H,” McDonnell Douglas Aerospace report MDC92E0008 (March 1992).