

# **Engineering Test Facility (ETF) for Heavy Ion Fusion**

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**Snowmass Fusion Study**

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**Snowmass talk based on previous talk:**

# **An Engineering Test Facility for Heavy Ion Fusion – Options and Scaling \***

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# Objectives of the ETF

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- **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 ( $> 40$  for a 25% efficient driver). Maximize yield in single shot tests (e.g.,  $Y > 100$  MJ may be possible with 2 MJ driver).
- **Driver** – Demonstrate driver technology with efficiency 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, steam generation, electricity production(?), and safe operation including recovery of tritium.

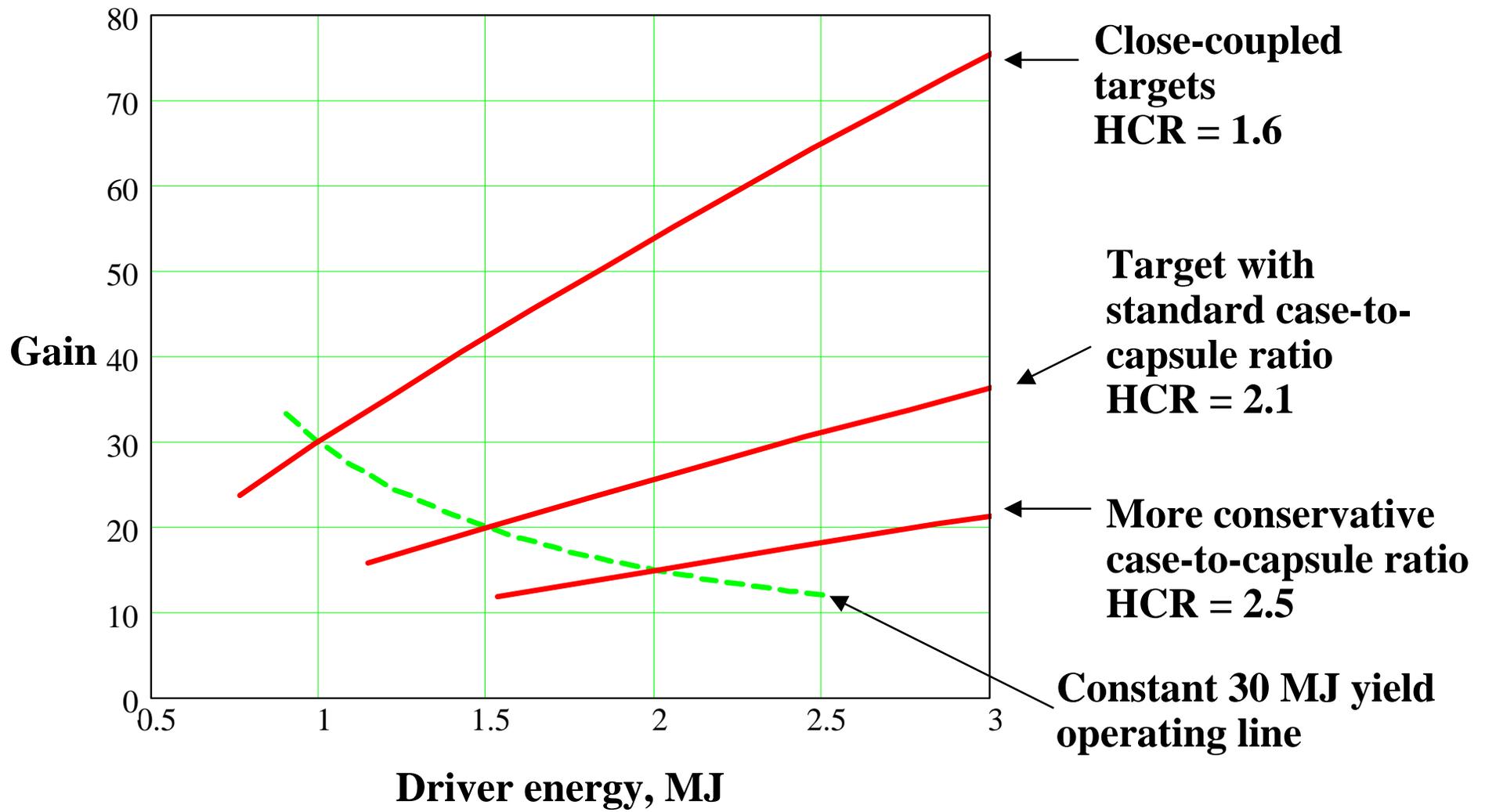
# ETF will progress through a series of increasingly difficult tests

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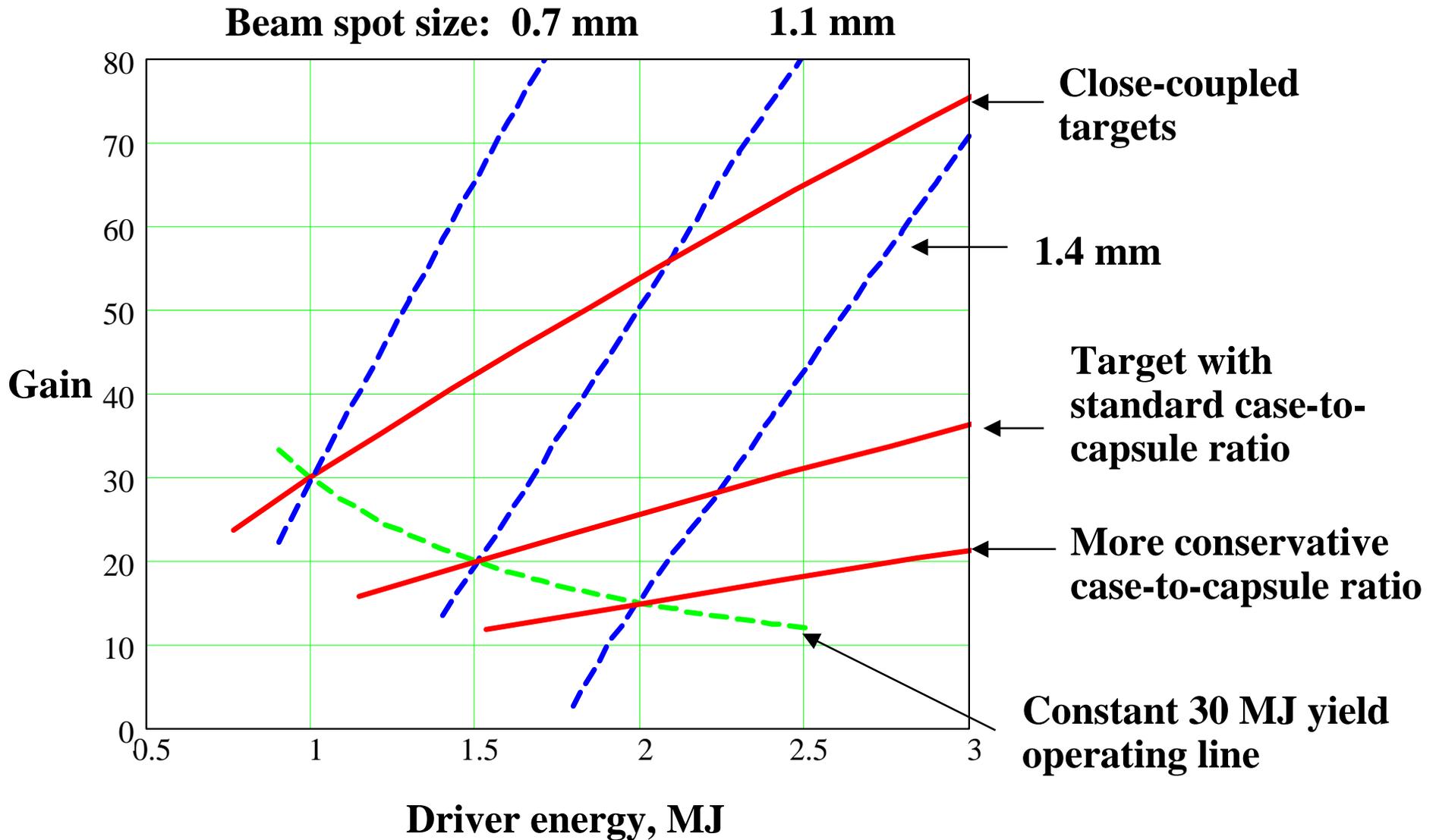


- High rep-rate driver operation with required efficiency
- Single shot, high gain target experiments to optimize target designs
  - first demonstration for heavy ion driver
- Short duration (minutes), burst mode tests at low yield to prove and optimize chamber designs
  - tritium breeding not required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

# Target gain for different hohlraum-to-capsule ratio (HCR) designs



# Driver energy and focusability will limit range of targets that can be investigated



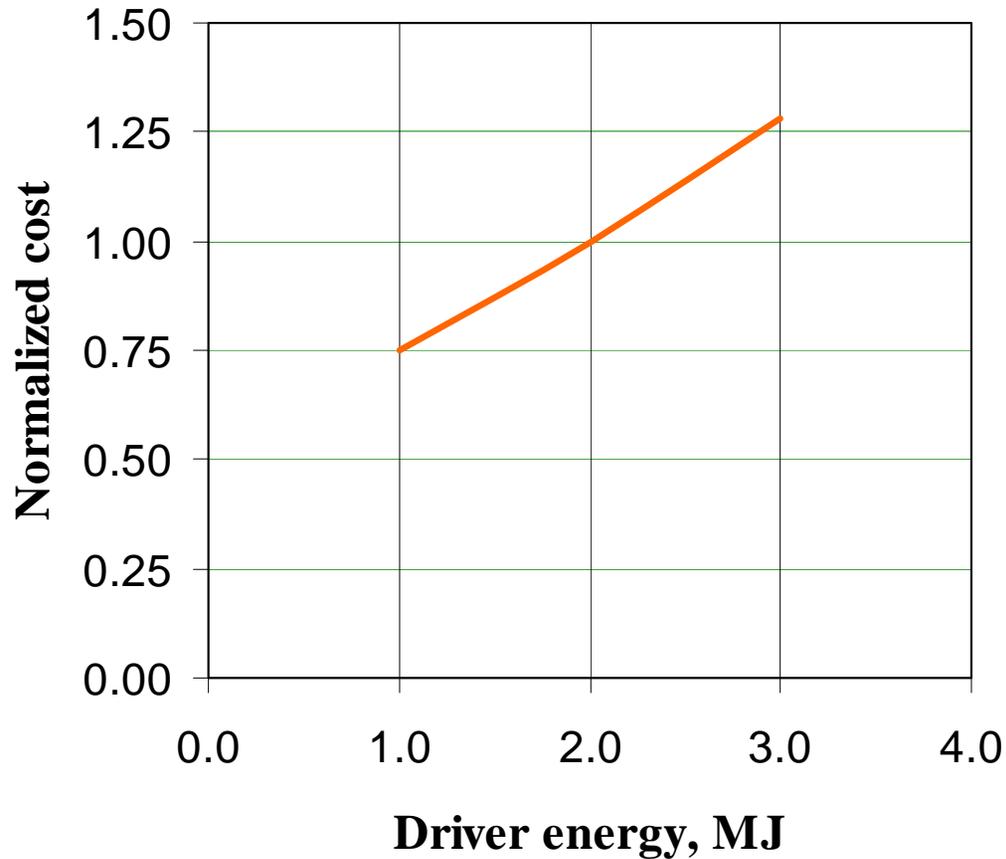
# Target scaling issues

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- Desirable to map out a significant part of target gain versus driver energy space, but capital costs will likely limit total available driver energy
- Power handling costs also favor lower yield targets, but low yield targets require small beam focus spot sizes (shorter final focus length for ETF helps somewhat)
- Smaller targets require capsules with better surface quality than full size targets, thus requiring production capabilities exceeding commercial power plant scale

# Driver costs scaling with driver energy



- **Relatively high buy-in cost:**  
reducing  $E_d$  by 50% to 1 MJ  
reduces cost by ~ 25%
- **Favorably scaling to higher energy:**  
increasing  $E_d$  by 50% to 3 MJ  
increases cost by ~28%

# ETF chamber dimensions and rep-rate are chosen to reproduce key phenomena

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- **Geometric scaling**
  - Key variable is target yield,  $Y$
  - Chamber, target injection, and driver/chamber interface dimensions reduced by a factor  $L$
  - $L$  scaling with  $Y$  chosen to optimally match different key phenomena
  - Some dimensions can be adjusted to improve fidelity (e.g. magnet standoff)
- **Millisecond phenomena**
  - Liquid/target motion: preserve relative effects of inertia and gravity
    - » Liquid/target velocities scale with  $L^{0.5}$
    - » Repetition rate scales with  $L^{-0.5}$
    - » Preserves liquid and target trajectories
  - Condensation on droplet sprays
    - » Droplet number density adjusted to preserve droplet heating ( $\Delta T$ )

# Key phenomena (cont.)

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- **Microsecond phenomena**

- X-ray ablation and debris venting
  - » Impulse loading effect on liquid trajectory ( $L \sim Y^{0.24}$ )
  - » Ablation layer thermodynamics and hydrodynamics ( $L \sim Y^{0.5}$ )
  - » Pocket energy density / coolant heating ( $L \sim Y^{0.33}$ )
- Neutron-heating induced liquid motion ( $L \sim Y^{0.4}$ )

- **Nanosecond phenomena**

- Target output x-ray and neutron spectra/deposition
  - » Lower capsule  $\rho r$  shifts more energy to neutrons (good)
  - » X-ray/debris energy partition tuned to adjust ablation mass
- Target/beam physics
  - » Most target/beam studies occur in single-shot chamber where initial conditions easily controlled and measured and diagnostic access is easier

# Key phenomena (cont.)

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- **Quasi-steady phenomena**

- Tritium and heat recovery/chemistry control
  - » Use single loop, full height, scale flow area with fusion power
  - » Adjust secondary blanket thickness to preserve tritium breeding
- Chamber thermal response
  - » Thermal stresses scale linearly with volumetric heating and  $L^2$
  - » Magnet standoff tuned to give acceptable magnet heating and target illumination geometry
- Chamber damage (activation/corrosion)
  - » Scaling accelerates damage due to increased fluence / coolant temperature)

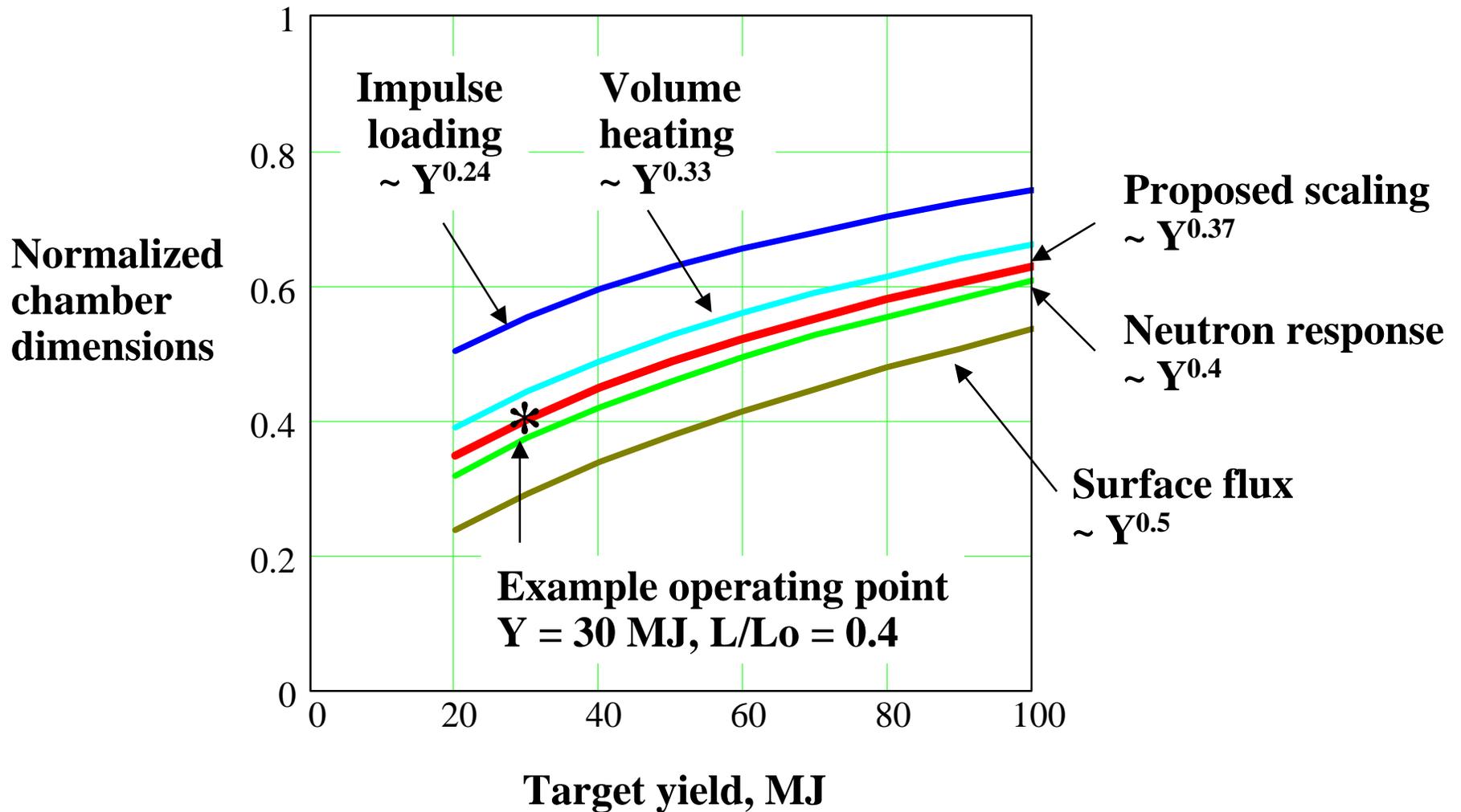
# Chamber dynamics can be investigated at reduced scale

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- For thick liquid wall chambers, there are a variety of non-dimensional parameters to scale various effects (e.g, surface flux, impulse loading, neutron induced motion)
- Scaling as  $(\text{yield})^{0.37}$  is proposed. The 0.37 scaling coefficient is midway between the 0.24 needed to preserve impulse loading and 0.5 needed to preserve debris induced thermodynamics and is close to the 0.4 needed to preserve neutron induced motion.
- For a 30 MJ ETF, all dimensions are reduced by  
$$L/L_0 = (30/350)^{0.37} = 0.4$$
- By varying the target yield about this design point, different chamber dynamics effects can be more closely matched

# Chamber scaling with target yield to match various effects

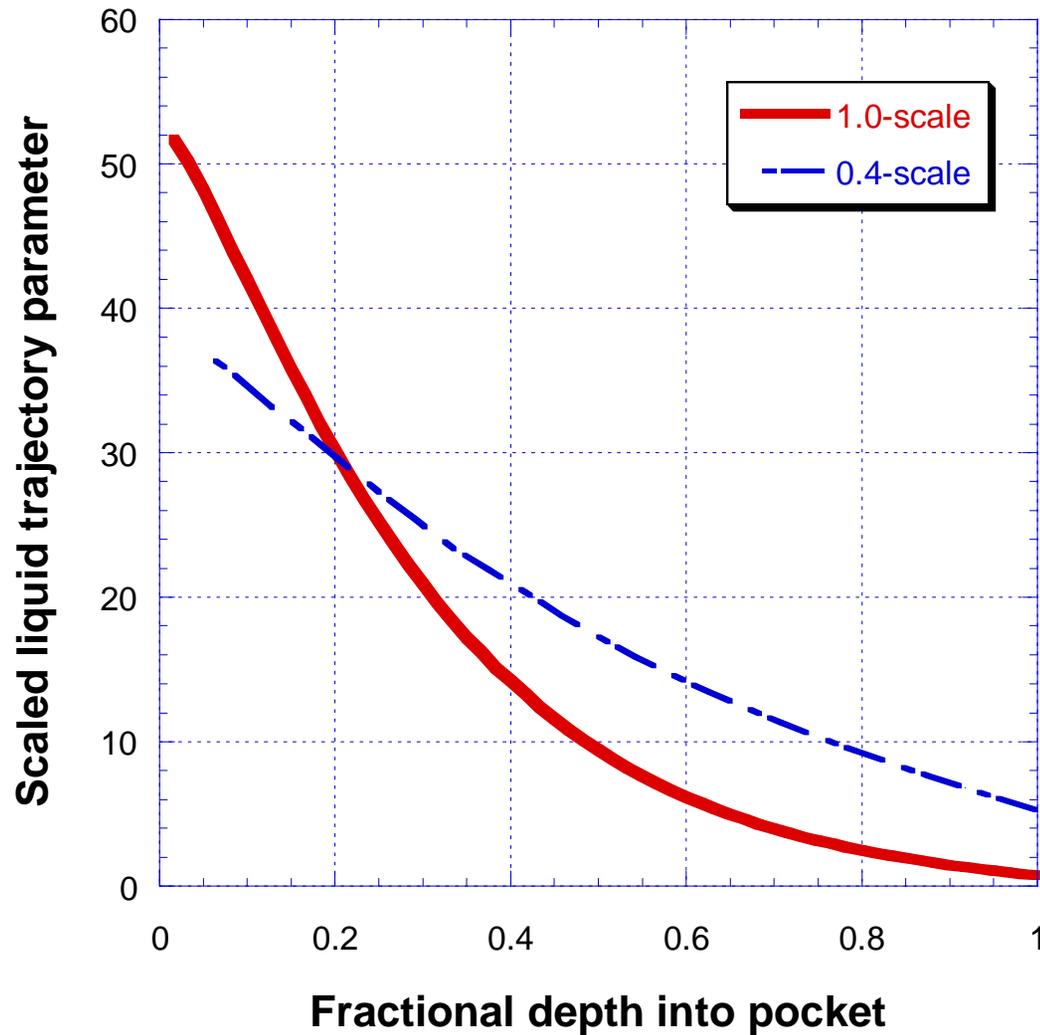


# Comparison of key nuclear parameters



|  | <b>ETF</b>           | <b>Power Plant</b>   |
|--|----------------------|----------------------|
| 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                  |
| 1st wall annual fast n <sup>o</sup> fluence (> 0.1 MeV), n/cm <sup>2</sup> -y        | $1.3 \times 10^{22}$ | $1.6 \times 10^{21}$ |
| 1st wall heating, W/cm <sup>3</sup>  | 166                  | 37                   |
| TBR (pocket/total)   | 0.55/1.23            | 1.18/1.26            |
| Magnets heating in coils, mJ/cc per shot   | 0.46                 | 0.07                 |
| Magnet annual fast n <sup>o</sup> fluence (> 0.1 MeV) to coils, n/cm <sup>2</sup> -y | $1.5 \times 10^{18}$ | $4.1 \times 10^{17}$ |
| Magnet annual dose, MGy/y  | 64                   | 1.5                  |
| Estimated magnet lifetime, years of operation  | 1.6-6.7              | 24-66                |

# Neutron induced liquid motion for 0.4 scale chamber compared to full scale



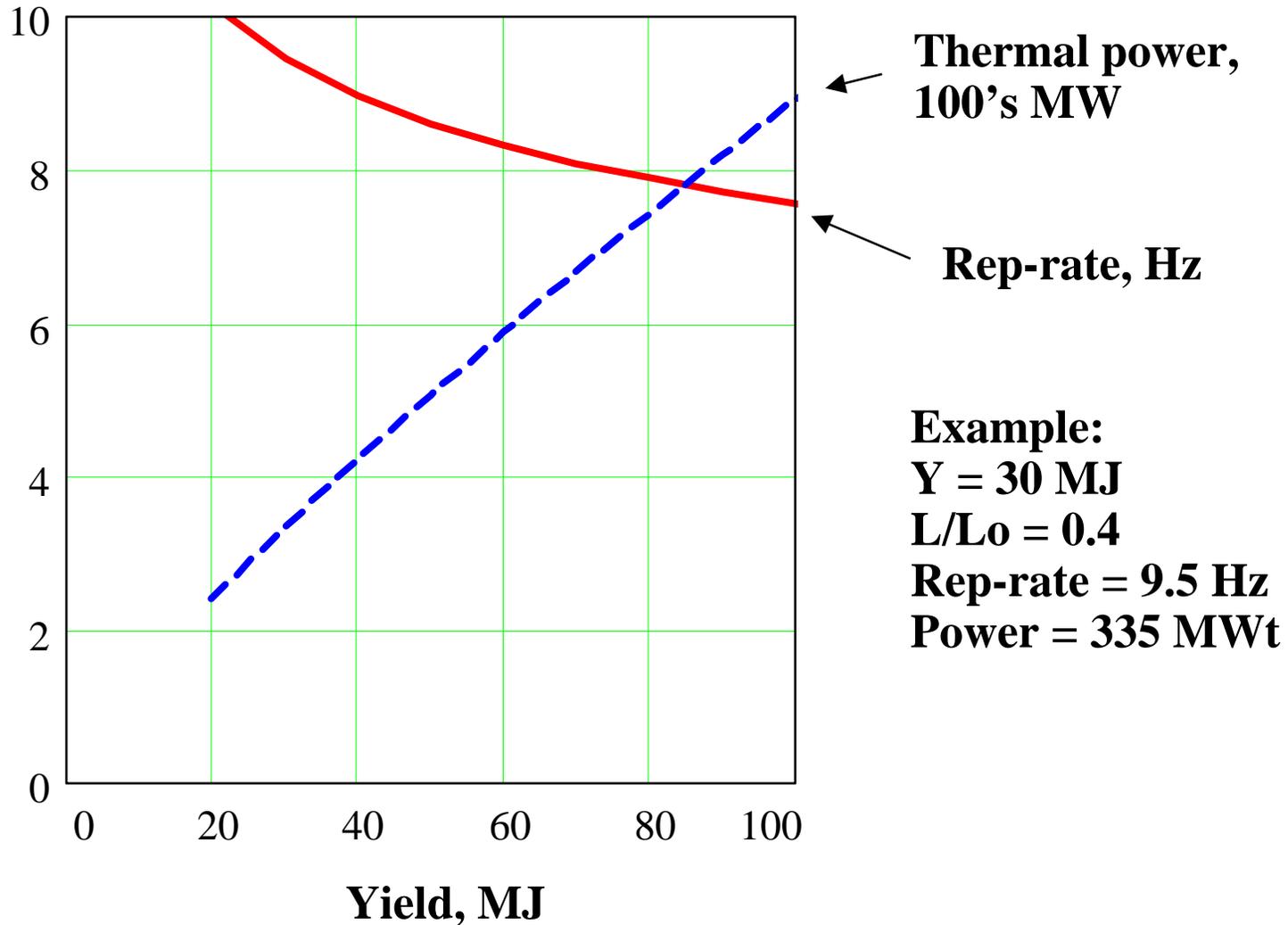
Scaled parameter is (J/g) divided by jet velocity:

$$\sim (J/g) / L^{0.5}$$

# Rep-rate and thermal power are determined by geometric scale



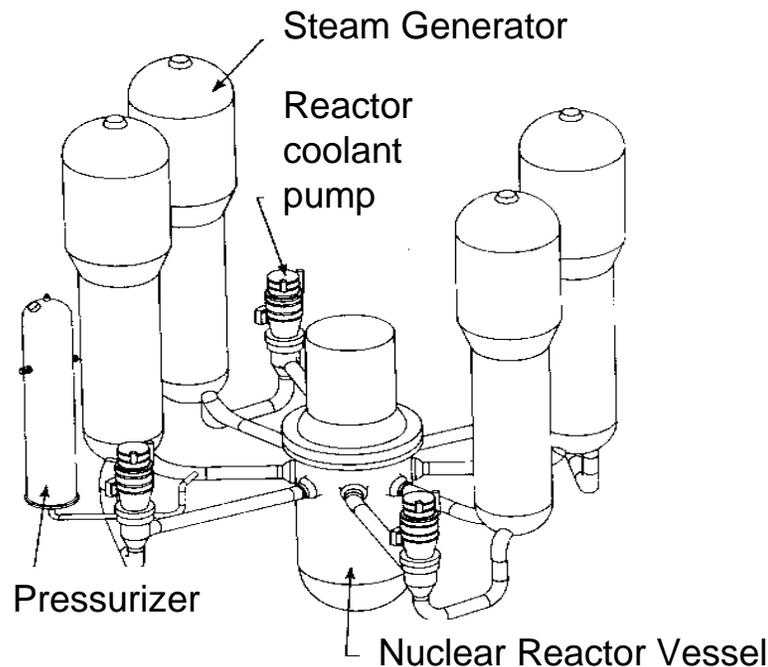
Results for  $Y^{0.37}$  scaling



# Heat transfer components can be tested at near 1/2 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  $\sim 1/2$  commercial scale
- Full length steam generator with fewer tubes will be used to preserve boiling effects.



Westinghouse 4-loop  
reactor coolant system

# Target fabrication and injection system requirements will be demanding

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- Target fabrication requirements will range from single-shot tests to batch mode to steady production
- Rep-rate and surface quality requirements will exceed commercial systems because capsules are smaller
- Because chamber scaling preserves the relative effects of inertia and gravity, the scaled targets will follow the same scaled injection trajectory, and the precision at shorter length should improve.
- Target size scaling with yield ( $Y^{0.34}$ ) is close to chamber/injector scaling  $Y^{0.37}$

# Example parameters for different driver energies and yields



| Driver energy, MJ | 2    |      |      | 3    |      |      |
|-------------------|------|------|------|------|------|------|
| Yield, MJ         | 30   | 80   | 100  | 30   | 120  | 200  |
| Gain              | 15   | 40   | 50   | 10   | 40   | 70   |
| HCR               | 2.5  | 1.8  | 1.6  | 3.1  | 2.0  | 1.6  |
| Spot size, mm     | 1.4  | 1.2  | 1.1  | 1.9  | 1.6  | 1.4  |
| Chamber scale     | 0.40 | 0.58 | 0.63 | 0.40 | 0.67 | 0.81 |
| Rep-rate, Hz      | 9.5  | 7.9  | 7.6  | 9.5  | 7.3  | 6.7  |
| Power, MWt        | 340  | 750  | 900  | 340  | 1040 | 1580 |

Low yield, Gain = 40 demonstration, Maximum yield for CCR = 1.6

# The ETF is a key step in heavy ion fusion development

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- Desirable to operate at small scale (e.g.,  $E \sim 2$  MJ,  $Y \sim 30$  MJ) for rep-rate tests to contain costs
- To access this operating space requires:
  - Target gain  $> 15$  with small capsules (but larger than NIF)
  - Beam focusing to small spot size ( $< 1.4$  mm)
  - Target production at higher rep-rate ( $\sim 9.5$  Hz) and precision than commercial systems
- The ETF will provide flexibility in developing HIF
  - Beam switching to multiple chambers (single shot and high rep-rate)
  - High yield ( $\sim 100$  MJ) tests and high rep-rate tests
  - Ability to varying target yield by varying target design (e.g., case-to-capsule ratio, tritium loading) and/or driver energy
- The ETF will define the path to Demo

# Summary of some key ETF points

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- **Subscale driver energy, but likely within 2x of driver**
- **Demonstrates high yield and gain for single shots**
- **Low yield for rep-rate tests to keep total thermal power and tritium inventory low**
- **Accelerated radiation damage testing**
- **After ETF phase upgrade driver to be driver for Demo**