Heavy Ion Fusion IFE Overall Plan*

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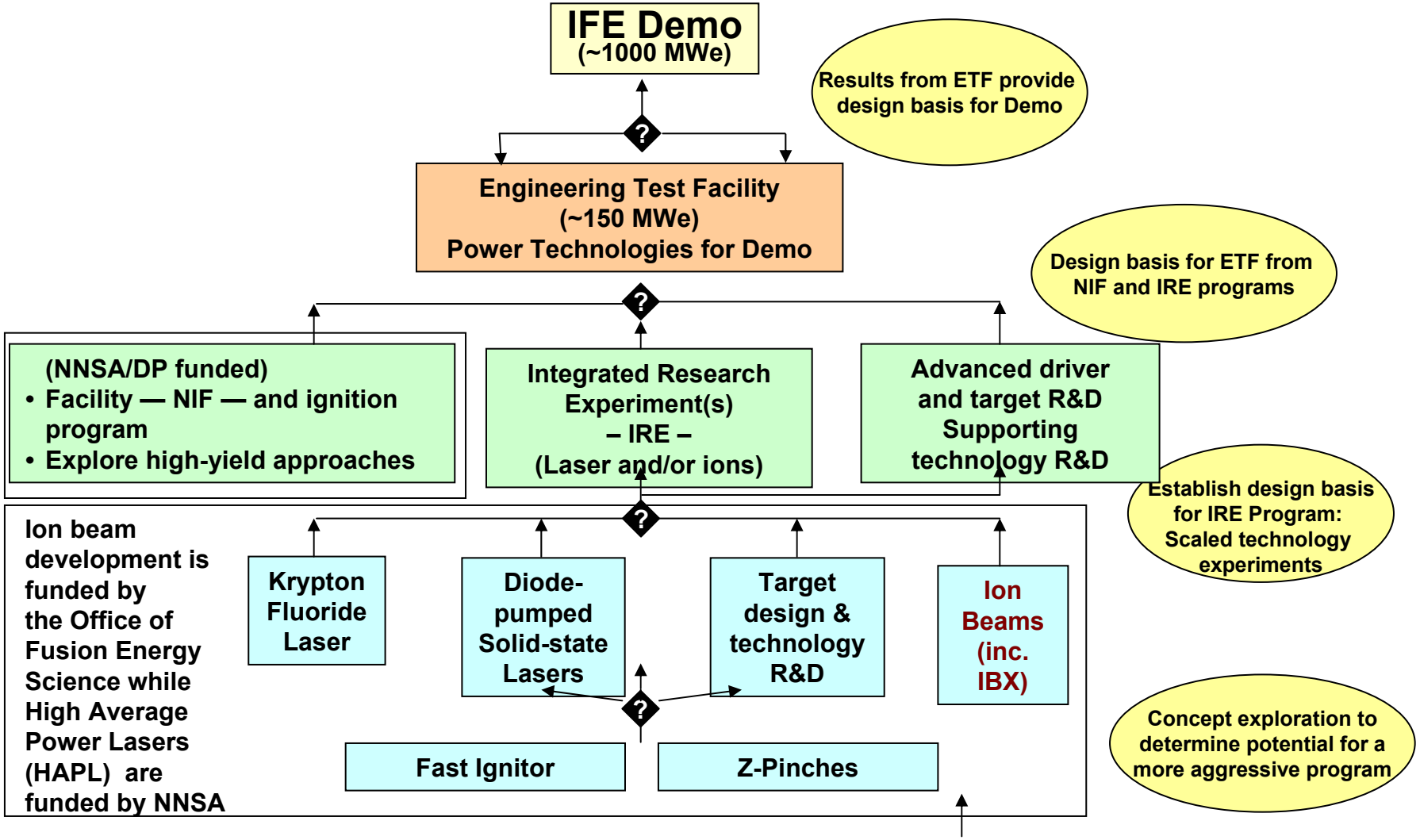
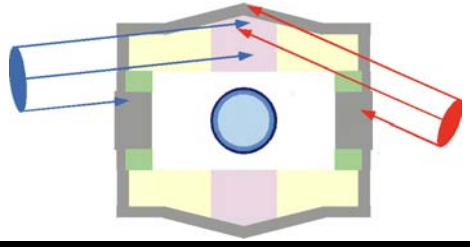
Heavy-ion strategy: Separate beam experiments, chamber and target R&D plus IBX will complete the proof-of-principle-level phase of research for HIF. The heavy-ion IRE, together with NIF and other R&D, would provide the basis for a heavy-ion ETF.



Reference HIF target requirements (Debra Callahan)



Requirement	Range
Total ion beam input energy	5 to 8 MJ (can vary size/ion range, 6.4 for ref design)
Ion range	0.035 g/cm2 (2.5 GeV Xe or equiv. for main pulse)
Number of beams	> 8 per end per angle (for azimuthal symmetry)
Pulse shape/symmetry- pre-pulse beams	25 to 45 % energy @ 75% range , 6-12 degrees, 30 ns
Pulse-shape/symmetry-main pulse beams	75 to 55 % energy @ full range, 12 to 24 degrees, 8 ns
Spot radius	2.3 mm for pre-pulse, 1.8 for main-pulse
In-flight aspect ratio	36
Capsule finish (nm RMS)	50-200
DT ice layer roughness (microns RMS)	1-5
Minimum fusion yield and target gain	> 200 MJ @ gain >25 for $\eta G>10$ @ calculated driver η of 48%, >350 MJ @ gain >50 for minimum CoE
Hohlraum material/density	Recyclable, cocktail, 1-100 % of solid density
Cost per target	~25 cents/target for acceptable CoE

Reference case HIF driver requirements

Driver requirement	Range
Ion mass	131 amu (for lower cost) to 238 (only if more margin needed on focusing spot)
Ion kinetic energy	2.5 to 5 GeV for mass 131 to 238
Number of beams	> 50 (to avoid excessive electric fields in final focus to ~ 100 for minimum cost based on SC quad transport
Beam energy to target	5 to 7 MJ total depending on desired yield/rep rate, ~ 30-40% of beams @ 75% full energy for pre-pulse,70-60% of beams @ full energy for main pulse
Ion source current/emittance/pulse	> 0.5 A/beam, < 2 π mm-mr normalized /, > 10 μsec
Transverse emittance growth at focus	< 5 p mm-mr normalized to meet focal spot size
Parallel momentum spread at focus	delta p /p < 5 x 10-3 to meet focal spot size
Electric-to-beam efficiency @ >5 Hz	> 20% for ηG > 10, > 40% for minimum CoE
Ferritic core material cost	< 5 $ /kg
Switching cost for >109 shot life	<10-5 $/Watt
Insulator cost	< 0.01 $ Volt @ meter diameter
Durability/reliability	> 10^9 shots between maintenance periods, sufficient for >75% overall plant availability

Reference HIF Chamber Requirements

Requirement	Range
Geometry compatible with reference target	One or two sided illumination with > 100 beams
Pulse rate	~ 5 to 7.5 Hz for CoE minimum depending on target gain and driver energy range
Lifetime for focus magnets and chamber	> 109 shots for overall availability > 75 %
Ballistic neutralized focus	Chamber pressure < 1 millitorr, maximum standoff for final focus < 6-8 meters
Focus array size	< 24 degrees for array half-angle
Beam focusing angle	~ 12 -15 mr
Coolant temperature	550 to 650 C for thermal conversion efficiency
Tritium inventory in chamber	< 150 g mobilizable T for safety
Annual waste production	< 1 m3/yr for class C and <0.01 m3/yr for above Class-C-level, assuming recycle
Maximum credible accident dose	< 10 mSv (1 rem)

Requirements for IRE and ETF for any IFE approach

Requirements to qualify IRE for each approach:

- Resolve key PoP driver issues that are specific to each approach
- Publish adequate gain IFE target designs with 2-D hydostability for plausible beam non-uniformities
- Plausible pathways for target fabrication and injection
- Chamber design concepts compatible with target illumination geometry, final focus and beam propagation

Requirements to qualify ETF for each approach:

- Adequate NIF target physics data
- IRE-level confirmation of scaling for ETF driver cost and lifetime at rep-rate, for adequate efficiency at minimum ηG
- Test injection of prototype ETF targets in simulated fusion chamber environment (could be separate facility)
- Final focus lifetime data for sufficient # of shots under prototypical ETF conditions
- Experiments that resolve specific issues of beams driving ETF targets (e.g., beam balance, symmetry, imprint, filamentation, chamber plasma/gas interaction)

Challenges to realize heavy-ion fusion

Success of heavy ion fusion energy requires understanding:

1. **Beam quality** for focus- emittance growth, electron/gas interactions at high current, evolution of beam distributions over long pathlengths
2. **Maximum-average beam current densities** achievable in injection, transport and acceleration experiments for future multi-beam arrays
3. **Longitudinal bunch compression** with velocity-tilt after acceleration
4. **Beam perveance** (beam space charge potential over ion kinetic energy) and **neutralization limits** to final focus and chamber transport

IBX will address much of issues 1-4.

The follow-on IRE would address

5. **Multiple-beam interactions** -electrostatic and magnetic beam-beam coupling in the accelerator, and when converging together in the chamber
6. **Innovation and integration of improved accelerator technology** for the compact multiple-beam injectors, compact superconducting transport magnet arrays, agile waveform solid state pulsers, low cost/ low loss ferromagnetic core materials, high gradient and low cost insulators.

Roles of the IBX and IRE in heavy-ion fusion strategy

IBX (~ $50 M): Use existing technology to expedite integrated beam physics: measurements and simulations of beam distribution evolution through injection, acceleration, drift compression, final focus and chamber propagation with plasma neutralization.

→ The role of the IBX is to increase confidence that the next step, the IRE, will be able to compress and focus beams to >TW/cm^2/beam sufficient to drive a variety of important ion chamber and target experiments.

IRE (~$250 M): Prototype multiple beam technology, efficiency, rep-rate at unit costs that scale to competitive power plant requirements. Drive several experiments: multiple beam chamber transport, target injection @5Hz bursts, foot-beam coupling and symmetry in hohlraums @ 100 eV.

→ The role of the IRE is to provide the basis for an ETF through improved accelerator technology integrated with chamber and target experiments (no-yield). *The IRE thus gives a key focus for heavy-ion chamber and target research in the program over the next 8-10 years.*

Goal: Integrated Research Experiment (IRE) for both *ion-specific target physics* and driver prototype technology

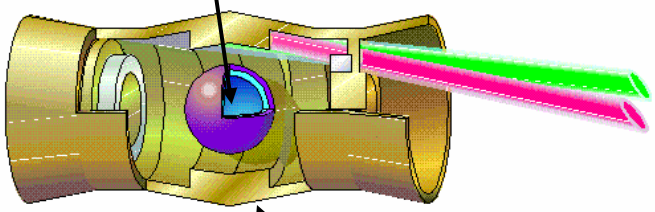
IRE: High intensity beam physics: multiple-beam effects, long-term transverse and longitudinal dynamics, etc...

HIF Target Design (LLNL-OFES)

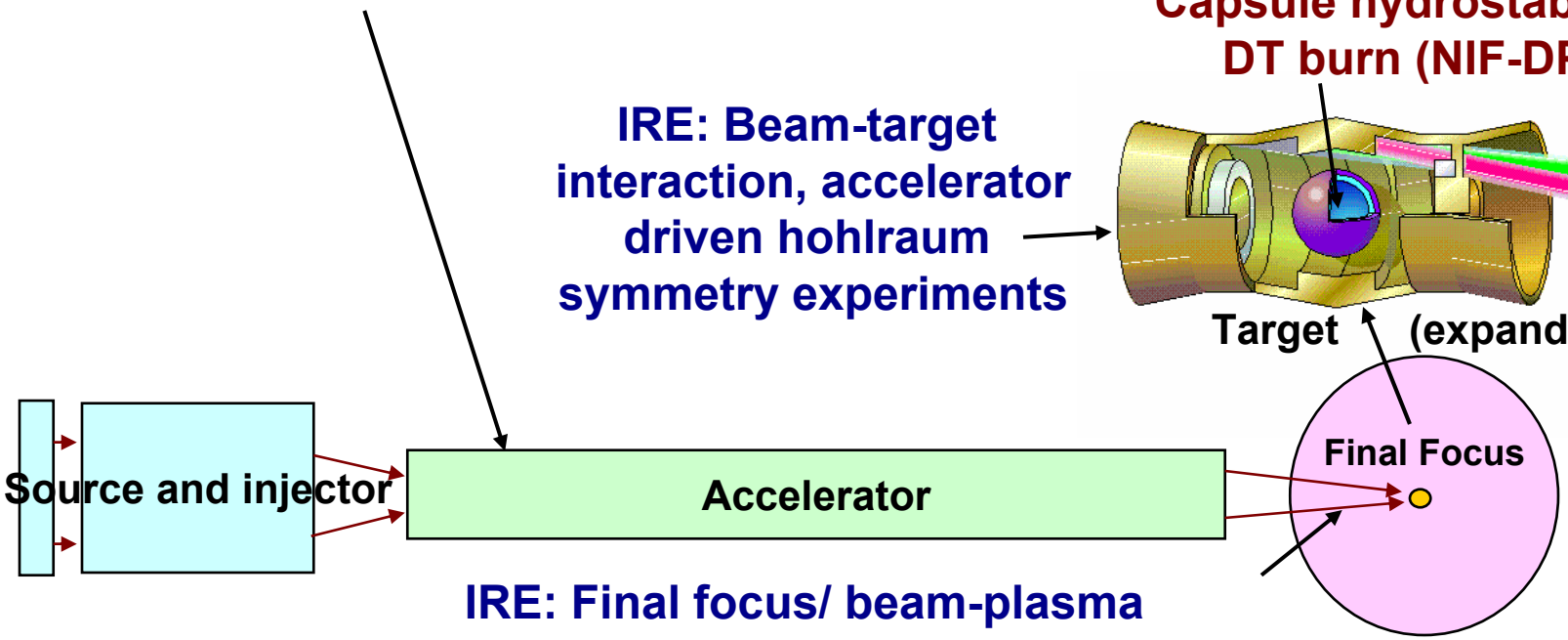
Injection/fabrication R&D (VLT-OFES)

Capsule hydrostability/ DT burn (NIF-DP)

IRE: Beam-target interaction, accelerator driven hohlraum symmetry experiments



Target (expanded view)



IRE: Final focus/ beam-plasma neutralization, to reduce ion energy and save money

Additional specific requirements for an HIF-ETF

1. IRE tests showing focal spot size predictive capability with multiple beams and plasma neutralization over 2- 4 meter focal lengths (Exp1).

2. Demonstrate multi-beam precision/coupling into scaled hohlraums that validate codes incorporating ion range shortening, and tests for other advanced HIF targets (Exps2).

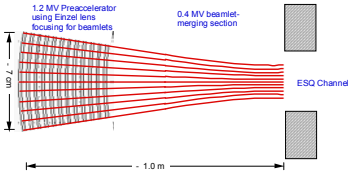
→An IRE capability for the second experiment will require high beam quality after large longitudinal bunch compressions, a high degree of plasma neutralization to reliably achieve small focal spots.

→ HCX, NTX, STS500 and IBX together with integrated modeling will provide the key experience needed for such IRE experiments.

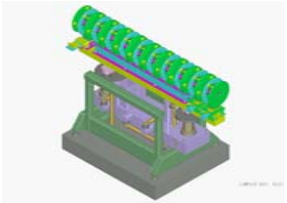
IBX + integrated modeling would add confidence in IRE target-shooting capability

NOW (next three years)

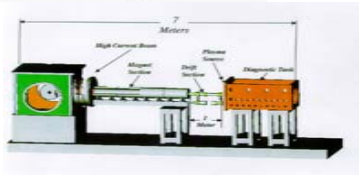
Brighter sources/ injector



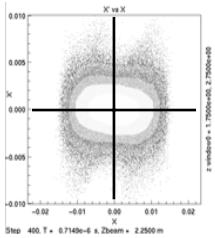
Maximum <J >, B_n Transport



Beam neutralization → min ε-limited focus r_f

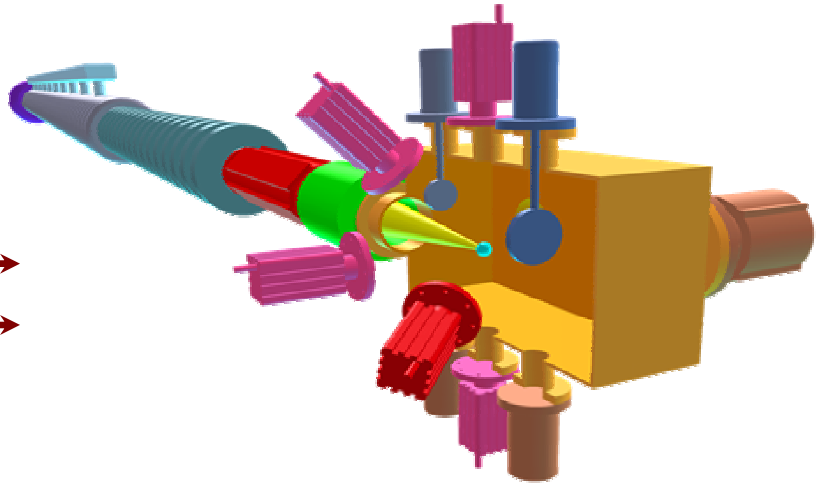


Theory/simulations



NEXT STEP

Integrated beam experiment (IBX)



Injection, acceleration, drift compression and final focus to test source-to-target integrated models

Current VNL HIF research and IBX would contribute important metrics for an HIF-IRE decision:

Completion of current research milestones through FY04:

HCX- quadrupole fill factors, effects of halo loss (electron/gas effects); NTX-geometric FF aberrations and plasma neutralization @ perveance range 10^{-4} to 10^{-3}; STS 500-high gradient insulator tests, merging-beamlet experiment, integrated modeling methods.

IBX-contributed metrics for an IRE decision:

- **Transport with low emittance growth for aperture fill factors > 0.5 and for > 40 - 80 lattice periods**
- **Average acceleration gradient > 0.5 x $E_{ion}/(eL_{bunch})$ V/m**
- **Final focus to near-emittance-size spots after > 5 x longitudinal bunch compression, beam perveance > 2 x 10^{-4}, and >90% plasma neutralization, consistent with predictions of integrated models.**

Other HIF research decision metrics for an HIF-IRE:

In addition to the current HIF experiments and IBX achievements, the IRE construction decision would require:

- **Peer-reviewed/published HIF target designs with adequate gain for $\eta G>10$.**
- **Compact multi-beam injectors with normalized emittance < 1 π mm-mr, and overall average current density > 30 A/m^2 adequate for IRE**
- **End to end simulation of a full scale driver**
- **Affordable technology for multiple beam linacs: low loss cores, high gradient insulators, solid state pulsers, SC quad arrays.**
- **Feasibility (plausible pathways) shown for low cost HIF target fabrication and injection**
- **Credible power plant concepts with feasibility data for long-lasting chambers and final focus interfaces compatible with driver and target requirements.**

Needed heavy-ion target R&D (design/fab/injection) -- working as a team:

1. Materials-activation/recycling/high opacity
2. Low cost fabrication-simplify design, new methods to make low density hi-Z foams
3. Capsule membrane supports-effect on symmetry, consistent with injection accelerations.
4. Try design for double pulse linacs (nice but not essential)
5. Seek ways to reduce or eliminate two energy beam sets (nice but not essential)
6. Develop shims for hybrid targets and for symmetry handle-(nice but not essential)
7. Optimize heavy-ion Hohlraum design for fuel compression (nice but not essential).

Heavy-ion chamber-FF interface research needs

1. Carry out scaled multiple jet disruption experiments to validate droplet clearing rates, and guide design to eliminate convergent shock-produced jets.
2. Identify methods to extract/recycle Hohlraum debris from molten salt.
3. Test short-pulse voltage breakdown of representative HIF FF beam-pipe with beam simulated by a central conductor-test with and without Flibe salt contamination.
4. Research alternative final focus magnets (e.g., HT superconductors) that can avoid high level waste (nice but not essential)
5. Explore conceptually large vortex chambers to see if reduced pumping power, higher pulse rates @ lower fusion yields and better magnet shielding can be obtained.

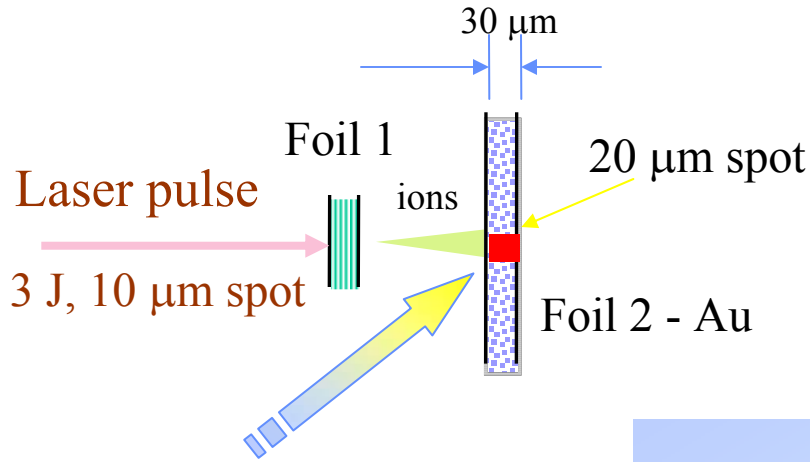
Heavy-ion Integrated Research Program needs:

- Innovation in design and funds for advanced technology development to reduce costs for the IRE by about ~3x from present technology projections.

- Expanded heavy-ion chamber and target R&D aimed to support integrated target shooting and chamber tests using the IRE that are important to provide confidence in the ETF.

- Explore heavy-ion beam target interaction physics at full power-plant intensities (several 10^{14} W/cm^2) using laser-produced, high brightness ion micro-beams, as a timely supplement to the IRE.

Laser-generated heavy ion beams can enable warm dense matter experiments in the nearer term before the IRE.



20 fs x-ray pulse from
all optical Thompson source

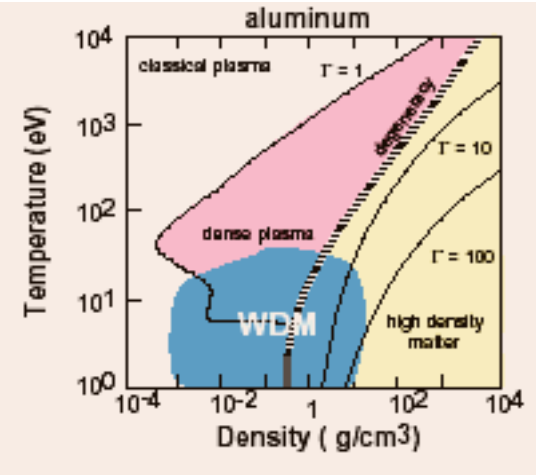
1 laser beam - 3 J

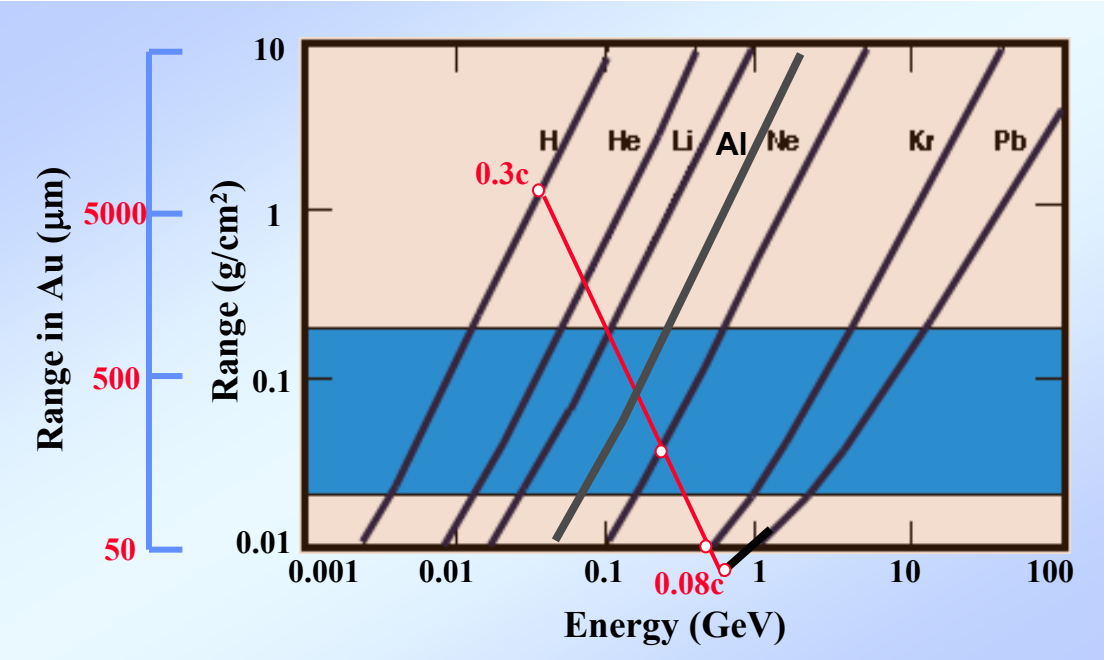
==> ~0.3 J heavy ions @ 3-5 MeV/n

==> ~10^5 J/cm^2 in ~1 ps

==> 10^5 TW/cm^2

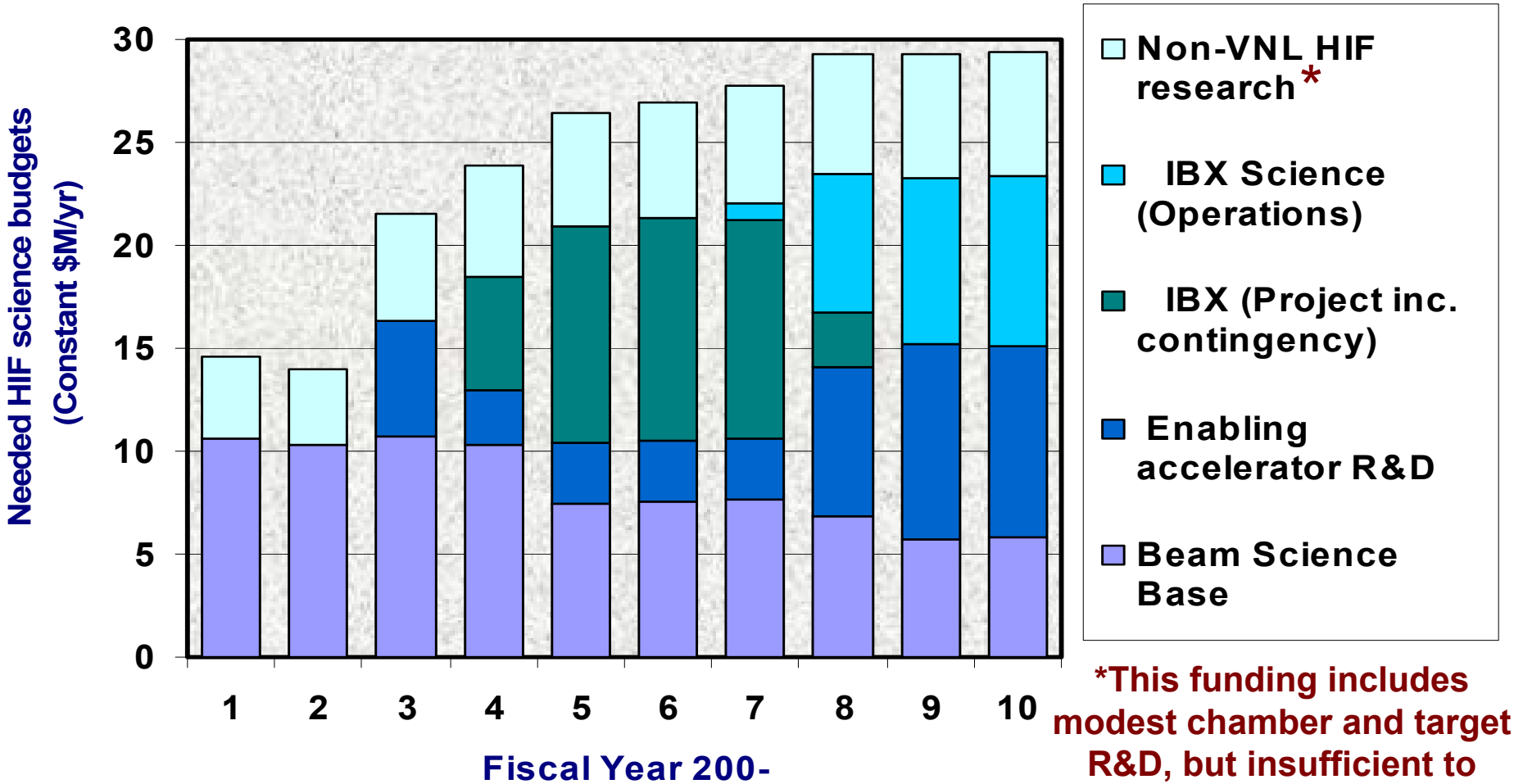
==> ~5×10^5 cal/g ==> ~50 eV





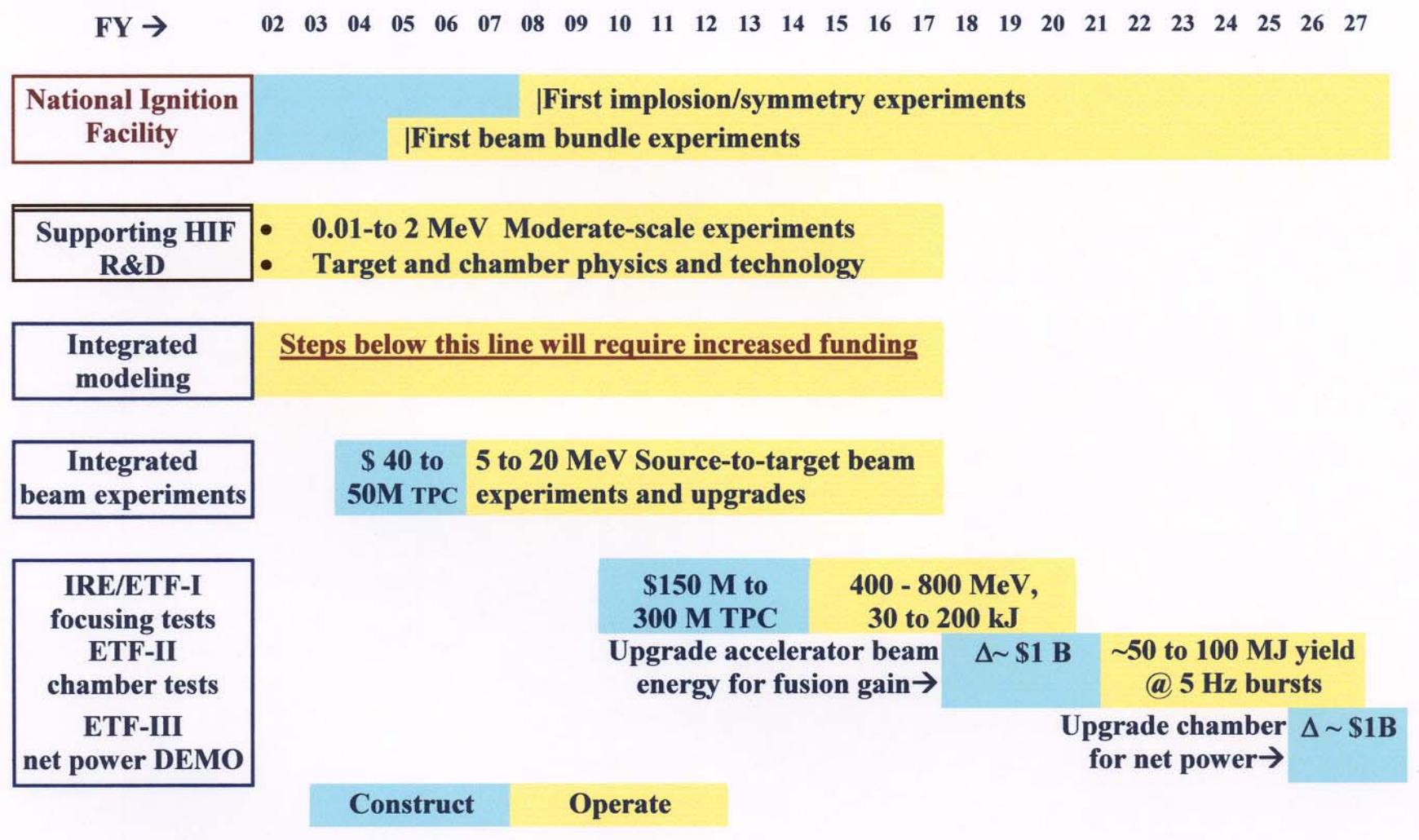
Extended National HIF Phase I (Proof-of Principle) Plan

[Assumes $45 M IBX with growth of national HIF to ~27M/yr]



*This funding includes modest chamber and target R&D, but insufficient to enable IRE/ETF by FY10.

Long- range HIF strategy to expedite an ETF



→ The expedited ETF schedule shown here would require faster IBX construction (3-yr vs. 5-yr), and more accelerator, chamber, and target support, than in the $27 M/yr plan.

Nominal top-level requirements for heavy-ion fusion

☞**Competitive cost-of-electricity < 5 cents per kWehr with acceptable environmental/safety characteristics, requiring**:

- **Multiple heavy-ion beams with range ~ 0.03 g/cm2 capable of delivering a total ion beam power ~0.5 PW for ~10 ns into r < 2 mm spots at ~ 5 Hz pulse rate for > 10^9 shots, with efficiencies > 20%, and direct capital cost < 1 B$.**

- **Manufacture of 500,000 heavy ion targets per day with gain > 50 at < 30 cents/target cost using materials that meet accident dose, waste management, and recyclability criteria.**

- **Long life chambers and final focusing magnets (> 3 x 10^8 shots) with low T inventory (<15 g for <1 rem worst case accident dose), and < 0.1 m^3 of long-term radioactive waste disposal per year.**