INERTIAL FUSION ENERGY DEVELOPMENT PLAN STRATEGY

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Secretary of Energy Advisory Board
Task Force on Fusion Energy
Third Meeting
Lawrence Livermore National Laboratory
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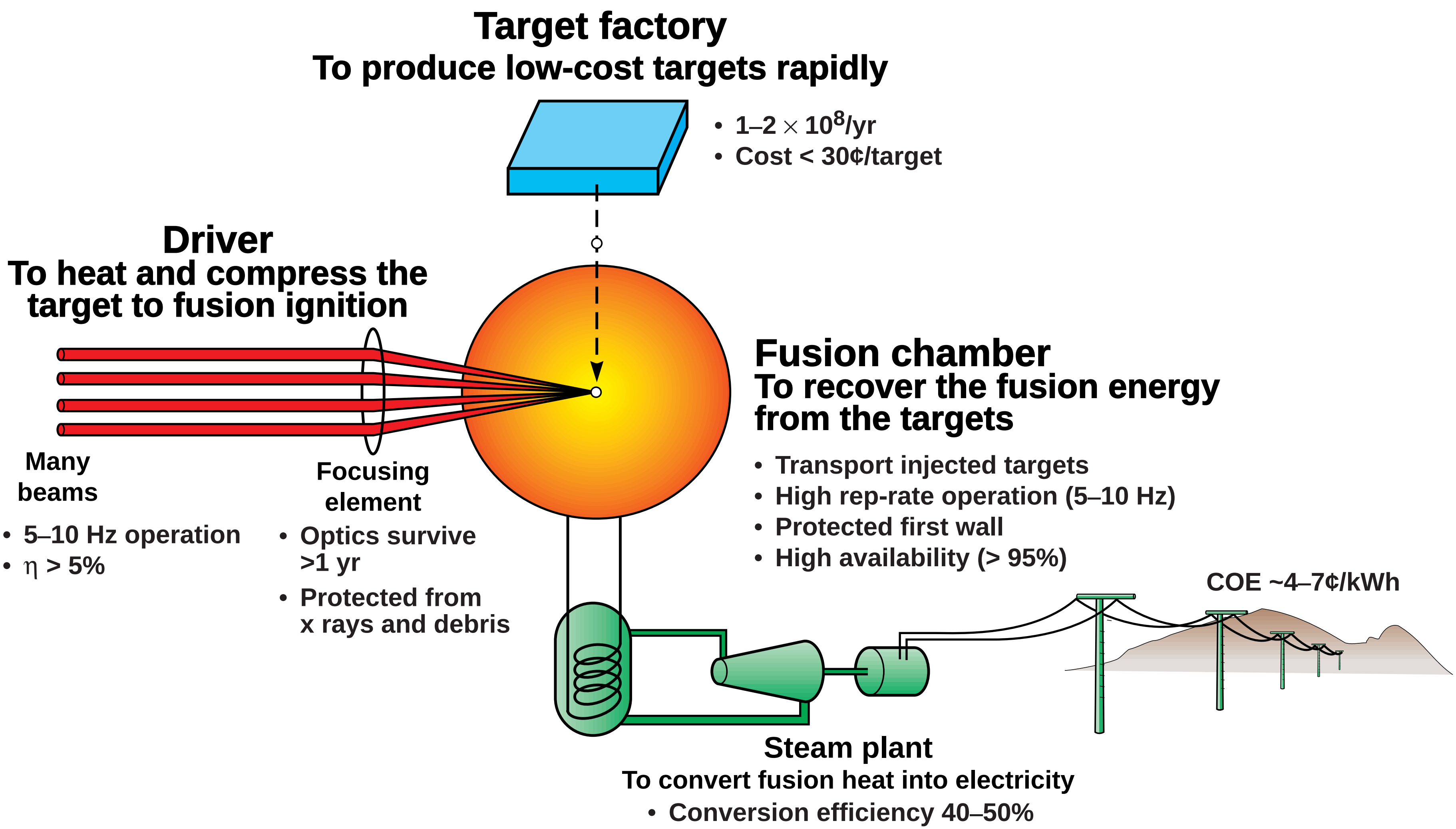
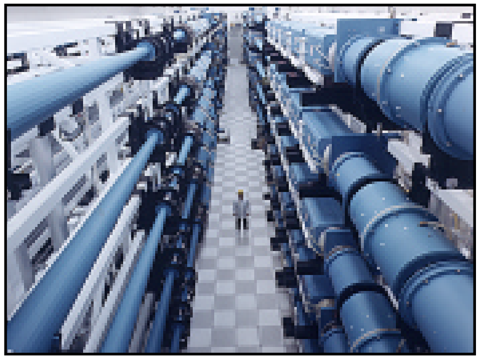
Summary/outline

- IFE provides a complementary approach to MFE
- DOE-Defense Programs support provides a significant and timely opportunity for developing IFE
- IFE satisfies requirements for fusion energy development
    - — Significant scientific/technological progress to demonstrating ignition and propagating TN Burn
    - — Fusion power plants which can satisfy cost, environmental and safety goals
    - — Phased delvelopment plan which balances risk and cost with deliverables and metrics
    - — Scientific and technological richness
- IFE portfolio approach allows breadth of options (drivers, target concepts, chambers) to be explored

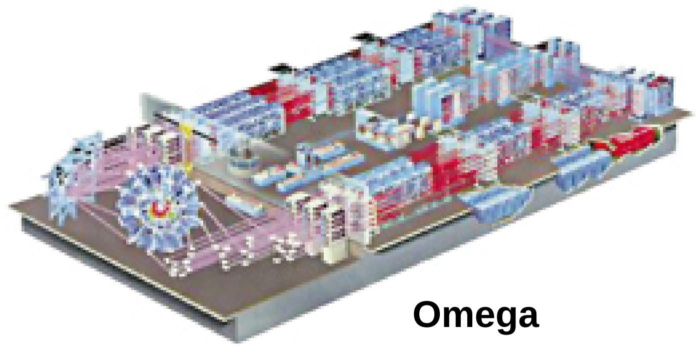
Inertial fusion energy (IFE) power plants of the future will consist of four parts



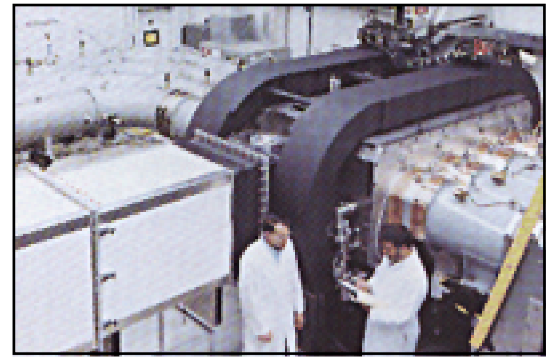
Inertial confinement fusion and high energy density science have been primarily developed in facilities constructed by DOE Defense Programs



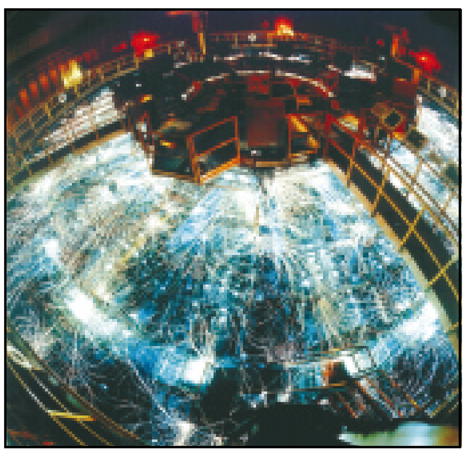
Nova (glass laser)



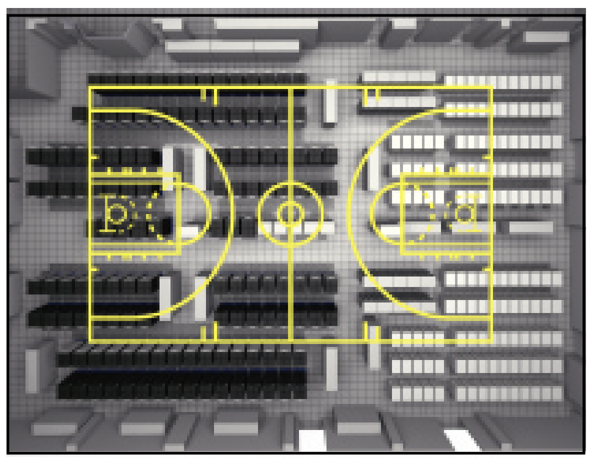
Omega
(glass laser)



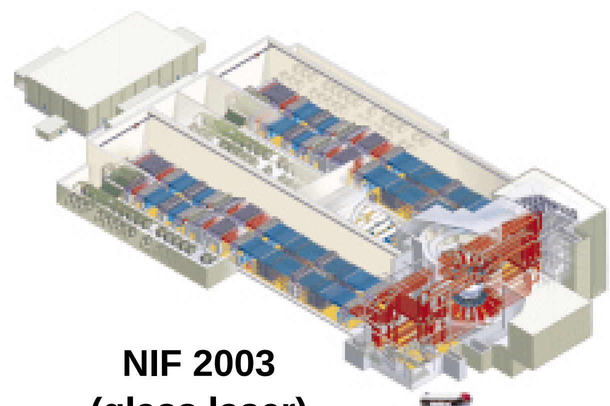
Nike (KrF laser)



Z! (light ions and Z pinch)



Multi-Teraflop Computers



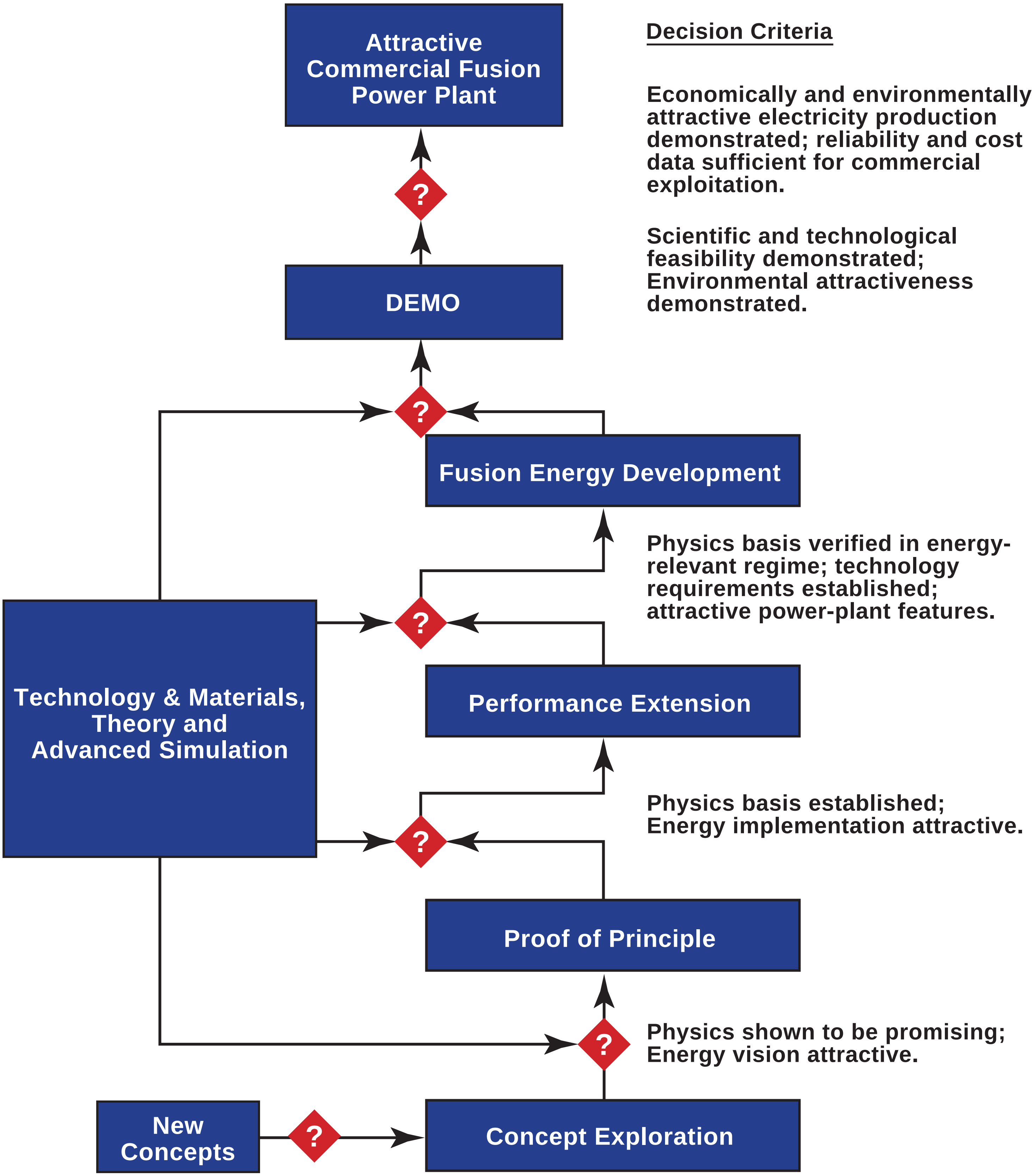
NIF 2003
(glass laser)

Significant contributions from international community (including OFES supported U.S. facilities) have also been made

Inertial Fusion Energy Development

- The fusion community (magnetic and inertial) has worked together to develop a road map for advancing fusion energy
- Road map essentials
  - Rollback from the "end product" goal
  - Broad portfolio that balances risk and expenditure and encourages innovation
  - Develops a common framework for all approaches (with recognition of differences in approaches)
  - Metrics to judge progress
  - Peer review
  - Assessment periods (next one in ~three–four years)

Levels of development roadmap



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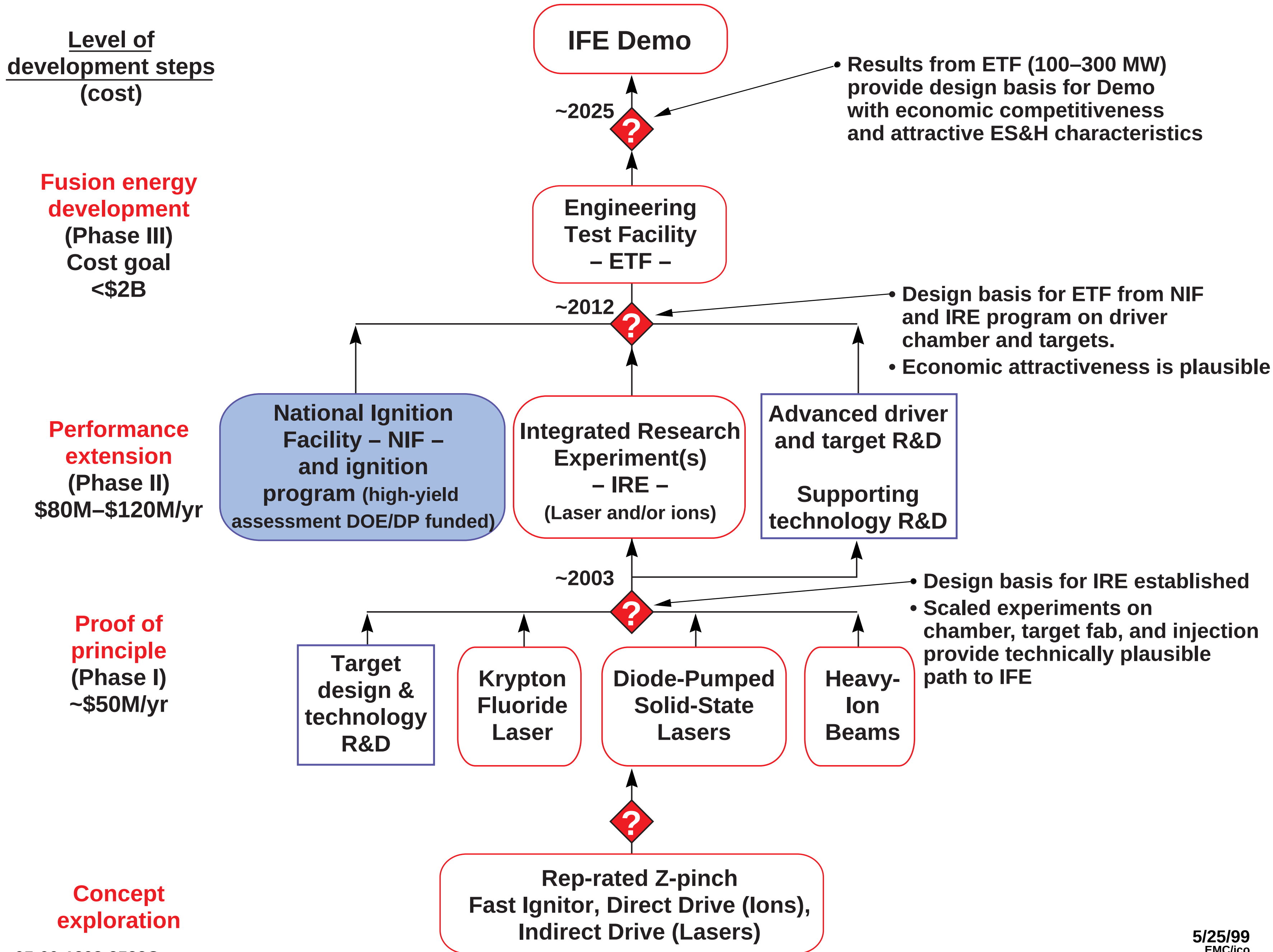
The Inertial Fusion Development Strategy is integrated with the Fusion Energy Road Map



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The IFE Program would engage the integrated fusion road map at three levels over the next 4–5 years

- Performance extension (DOE DP funded)
  - — NIF construction completion
- Proof of principle
  - — Electra (KrF) and supporting science/technology
  - — Mercury and supporting science/technology
  - — Heavy ion science/technology
- Supporting science/technology
  - — Chamber designs/materials
  - — Target fabrication and injection
- Concept exploration
  - — Fast ignition
  - — Rep-rated Z pinch
  - — Ion concepts (variable ion mass, target concepts)
  - — Indirect drive with lasers

Deliverables (with budget requirements) for all areas have been developed for Phase I

The Phase 1 goals for HIF have been developed

	NOW	Phase 1 goals	Power plant
Beam experiments	~10 mA; ~1 MeV; correct dimensionless parameters	~1 A; 1–10 MV; preserve	~1 A/beam[a]; > 1 GeV; adequate brightness
Injector	1A, 1 beam	~1 A/beam multi-beam module	~1 A/beam, multi-beam injector
Component technology unit costs	~3× higher than driver goal	~2× higher than driver goal	~$0.5 B
Simulation	End-to-end in 2-D; sections in 3-D	End-to-end in 3-D	End-to-end in 3-D
Longevity Efficiency Predicted COE	~10^8 pulses ≥25% projected ~5¢/kWh	~10^9–10^{10} pulses ≥25% projected ~5¢/kWh	10^{10} pulses ≥25% projected ~5¢/kWh

[a] At the beginning of the machine. Current increases with increasing kinetic energy.

Budget $72M

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The Phase 1 goals for KrF have been developed

Parameter	Current Status	Deliverables (Phase 1)	Power Plant
Laser bandwidth	3.0 THz	2.0 THz	1–2 THz
Single beam nonuniformity (high modes)	1%	1%	~1%
Overall efficiency	1.5%	6%	> 5%
Overall mean shots between maintenance	N/A	10^5	$\sim 3 \times 10^8$
Lens damage threshold	3 J/cm^2	10 J/cm^5	~ 10 J/cm^5
Mirror damage threshold	3 J/cm^2	15 J/cm^5	~ 15 J/cm^5
Amplifier aperture	60 cm	30 cm	100 cm

Integrated budget $73M

The Phase 1 goals for DPSSL have been developed

Parameter	Status	Phase 1	Power Plant
Overall system efficiency	No comparable system	10%	>5%
Diode efficiency	45% is routine	55%	55%
Diode cost	$\$3.00/W_{peak}$	$\$0.50/W_{peak}$	$\$0.07/W_{peak}$
System reliability	Mercury is first fusion DPSSL	$> 10^8$ shots	$> 10^9$ shots
Beam smoothness	7% (single beam)	0.1–1% on-target	0.1–1% on-target
Crystal size	3 cm	15 cm	15 cm
Frequency conversion to 3ω	80%	80% at 10 Hz with beam smoothing	80% at 10 Hz with beam smoothing

Budget $43.5 M

During Phase I, the chamber S & T Program would address key IFE issues—Heavy Ion IFE

Issue	Phase I Deliverable
Chamber clearing dynamics	• Demonstration of clearing with properly scaled liquid model experiment
Final focus/ chamber interface	• Magnet/chamber design with required shielding and focusing
Safety & environmental	• Minimize radioactive waste (shallow burial) • Designs with <1 rem dose at site boundary
Target fabrication and injection	• Fabrication of prototype target components • Demonstration of injection and tracking of warm targets • Prediction of survival of cryo targets in hot chamber

- Numerous facilities would be employed (large and small scale)
- Budget $31.5 M

During Phase I, the chamber S & T Program would address key IFE issues—Laser IFE

Issue	Phase I Deliverables
First wall/ chamber lifetime	Assess: • Carbon and SiC first-wall life • Effectiveness of Xe gas protection • Erosion rates for granular solid coolants • Rapid first-wall change-out procedures
Final optics survivability	Measure: • Hot-fused silica neutron irradiation damage • Grazing incidence metal mirror performance • Shock effects
Safety & environmental	Determine: • T_2 inventories in high-temp. carbon composites • Designs for <1 rem dose at site boundary • Activated dust transport
Target fabrication and injection	• Fabrication of prototype target components • Demonstration of injection & tracking of warm targets • Prediction of survivability of cryo capsules

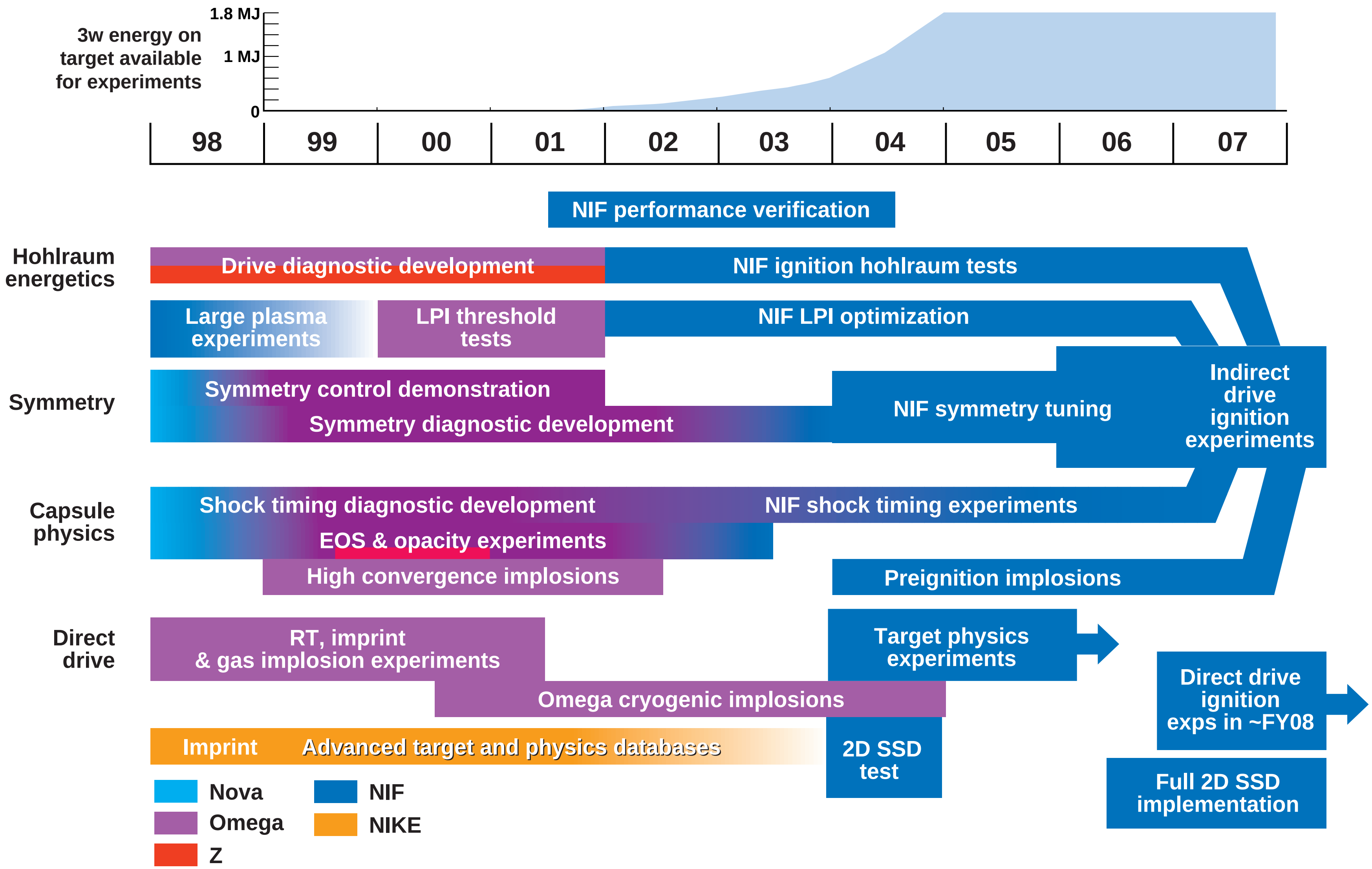
IFE Program status in 2003/2004

- Phase I deliverables

- DP funded activities
  - — Target physics at Omega, Z, and NIKE
  - — Fabrication of ignition targets
  - — NIF project completion
  - — Evaluation of utility/value of high yield targets for DOE (SSP and IFE) with pulse power and/or NIF

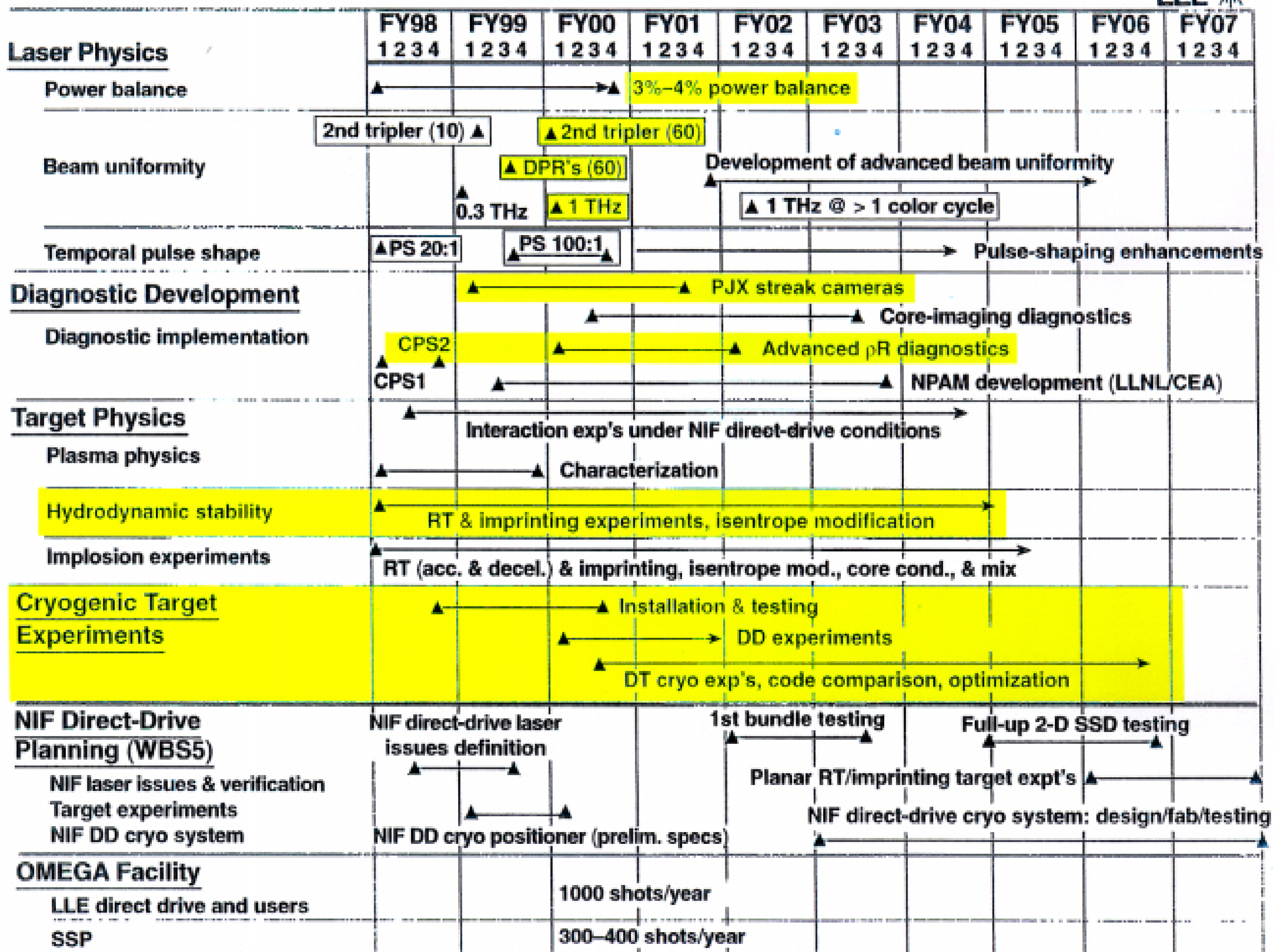
A national ignition plan has been developed to prepare for ignition on NIF

NRL • LLNL • SNL
UR/LLE • LANL • GA



UR LLE
NRL
GENERAL ATOMICS
Los Alamos
Los Alamos National Laboratory

LLE'S Long-Range Program Plan



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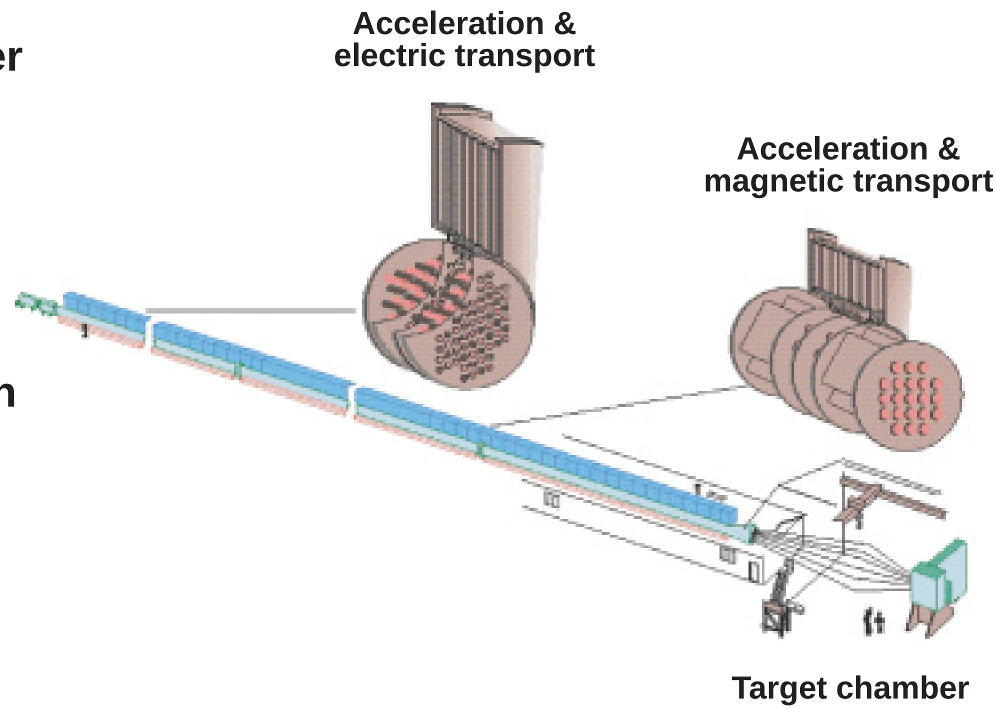
After the successful completion of “Phase I” IFE research, the program would be prepared to move forward

- Integrated Research Experiment
  - Demonstration of a full laser beamline
  - Integrated HIF experiment
- Develop and test high-pulse rate capable chamber and target systems
  - Injection and tracking capable of meeting IFE requirements
  - Protection of final optics and first wall
  - IRE may contribute to this area
- Development of mass production techniques for IFE targets
- Appropriate cost reduction activities to meet IRE and ETF goals

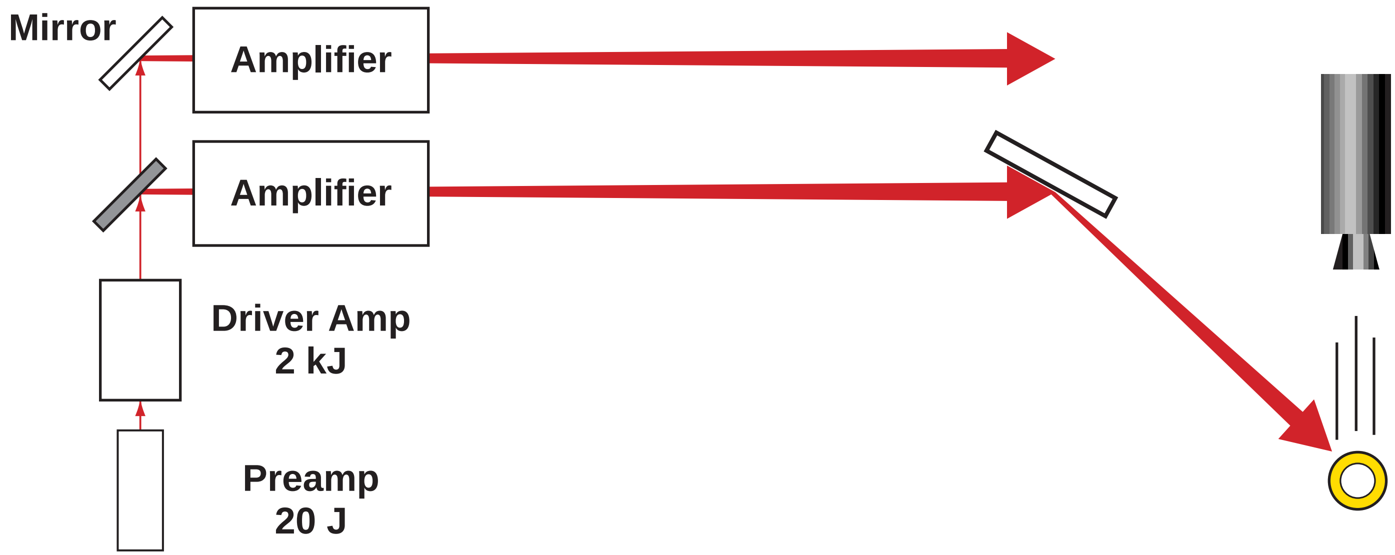
Concepts for an HIF IRE have been developed

- **Scale: Current per beam same as driver; final energy ~ 1/10 driver**
- **Beam quality: 6D phase-density same as driver; (e.g. corresponds to ε_N < 5 mm-mrad; $\Delta p/p < 10^{-2}$; Δt = 5 ns at T = 200 MeV)**
- **Chamber transport: neutralization ~90–95% with absence of destructive instabilities**



Achievement of goals leads to ~10^{15} W/cm^2 at driver beam energy

Concepts for a KrF IRE have been developed



Output/shot	50–150 kJ[(1)]
Efficiency	6–7%
Rep-rate	5 Hz
Durability (shots)	3×10^8
Lifetime (shots)	10^{10}
Projected laser cost	$180/J (laser)
Beam uniformity	Goals met
Beam power balance	2%
Optics damage threshold–lenses & mirrors	8 J/cm^2
Final optic lifetime (neutrons, x-rays, laser)	3×10^8
Beam steering	TBD[(2)]
Laser propagation in reactor environment	TBD[(3)]

As determined by Phase I...
(1) KrF studies
(2) Target injection studies
(3) Reactor studies

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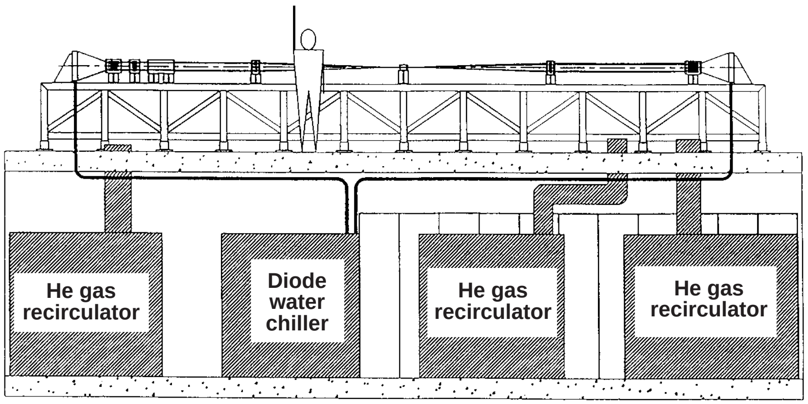
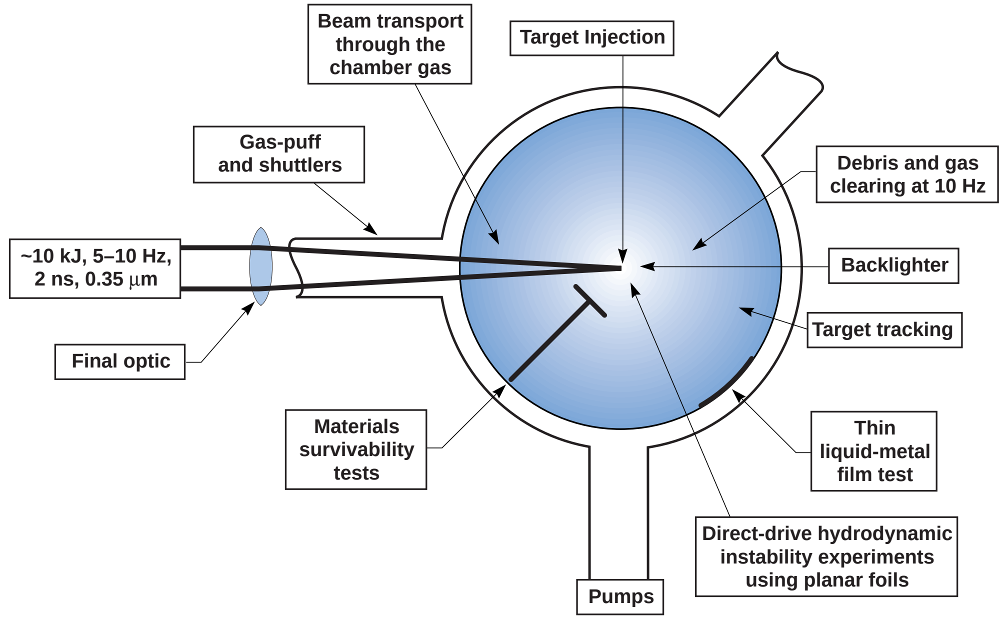
Concepts for a DPSSL IRE have been developed





- **Demonstrate laser beamline**
  - — performance
  - — lifetime
  - — cost scalability
  - — efficiency
- **Demonstrate laser/target and laser/chamber interface**
- **Conduct chamber technology tests**

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Sponsorship of both DOE-DP and DOE-OFES is required to fully develop Inertial Fusion Energy

Topic	*Sponsorship* DP	OFES	*Comments*
Target Physics			
• ignition/propagating burn	√		DOE-DP evaluating high-yield applications
• high gain		√	
Driver Science/Technology			
• single shot/peak power	√		
• rep rate		√	
• efficiency		√	
• cost	√	√	
Target Fabrication			
• "existence proof"	√		Requires only ~10^2–10^3/yr
• mass production/cost		√	
• injection	√	√	DOE-DP may explore on NIF to reduce collateral effects
Chamber			
• single-shot operability	√		
• cost, safety, operability, environment		√	

Bottoms-up Phase I IFE budget example

Costing, in $K

Topic	FY1999	FY2000	FY2001	FY2002	FY2003
1. KrF Lasers	*(DP)* 7,500	20,000	19,200	13,300	13,000
Electra laser	5,900	9,700	11,400	6,000	6,000
KrF physics	700	1,650	1,650	1,750	1,400
Front end	500	1,850	1,850	1,250	800
Coatings	250	2,100	2,200	2,200	2,200
System studies	150	1,700	2,100	2,100	2,600
Laser-target designs	*DP funded*	*DP funded*	*DP funded*	*DP funded*	*DP funded*
Laser-target experiments	*DP funded*	*DP funded*	*DP funded*	*DP funded*	*DP funded*
Computer (for 3D Target Design)	—	3,000	—	—	—
2. Solid State Lasers	*(DP)* 2,000	10,250	10,350	10,450	10,450
Efficiency	200	750	750	750	750
Diode cost	250	2700	2700	2700	2700
Beam smoothing/ physics impact	150	1300	1400	1500	1500
Gain media	0	2250	2250	2250	2250
Frequency conversion	100	950	950	950	950
Wave-front correction	0	500	500	500	500
Technology integration	1,300	650	650	650	650
Scalability	0	1150	1150	1150	1150
Laser-target designs	*DP funded*	*DP funded*	*DP funded*	*DP funded*	*DP funded*
Laser-target experiments	*DP funded*	*DP funded*	*DP funded*	*DP funded*	*DP funded*
3. Heavy Ion Accelerators	8,350	13,000	17,000	17,000	17,000
Beam Experiments	1,970	2,600	3,800	2,200	1,400
Injector	1,300	2,800	3,650	2,150	2,000
Enabling Technologies	1,460	2,850	4,100	4,000	1,950
Theory and Simulations	3,070	3,250	3,450	3,650	3,650
RDAC and other pre-construction	0	500	1,000	4,000	7,000
Ion Target Design	550	1,000	1,000	1,000	1,000
4. Chamber Systems	1,585	7,200	7,400	7,800	7,800
Heavy Ion Chamber	752	1,800	1,800	1,800	1,800
Laser Chamber	497	1,800	1,800	1,800	1,800
Target fabrication /injection	200	2,900	3,100	3,500	3,500
Safety & Environment	136	700	700	700	700
TOTAL IFE FUNDING ($K)	10,000 (OFES)	50,450	53,950	48,550	48,250

Why is such an OFES Program warranted now?

- Scientific and technical progress in ICF provides sufficient confidence now that IFE can be achieved
  - — Risk/development cost are balanced
- The proposed OFES Program *effectively* leverages the DOE-DP Target Physics Program
  - — DOE-DP has increasingly focused on target physics with reduced effort on science and technology relevant to IFE (drivers, chambers, innovative concepts)
- "Waiting for Ignition" will delay the development of IFE by a decade and prevent the capitalization of resources developed by DOE-DP
- Science and technology challenges and history give high confidence of continued benefit outside of main mission

Peer review (internal and external) and the entire fusion community working together are essential elements of the Program

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