The World Energy Problem - What Should We be Doing?

FPA Annual Meeting, Washington 2005

"Energy Options for the Future," John Sheffield, Steve Obenschain et al, J. Fusion Energy, 23, 2, 63, 2004.

"Survey of World Energy Resources," WEC 1995 and 2004.

"Possible Strategies for a Broadened Fast Track Approach to Fusion Energy," Dale Meade, SOFE 2005.

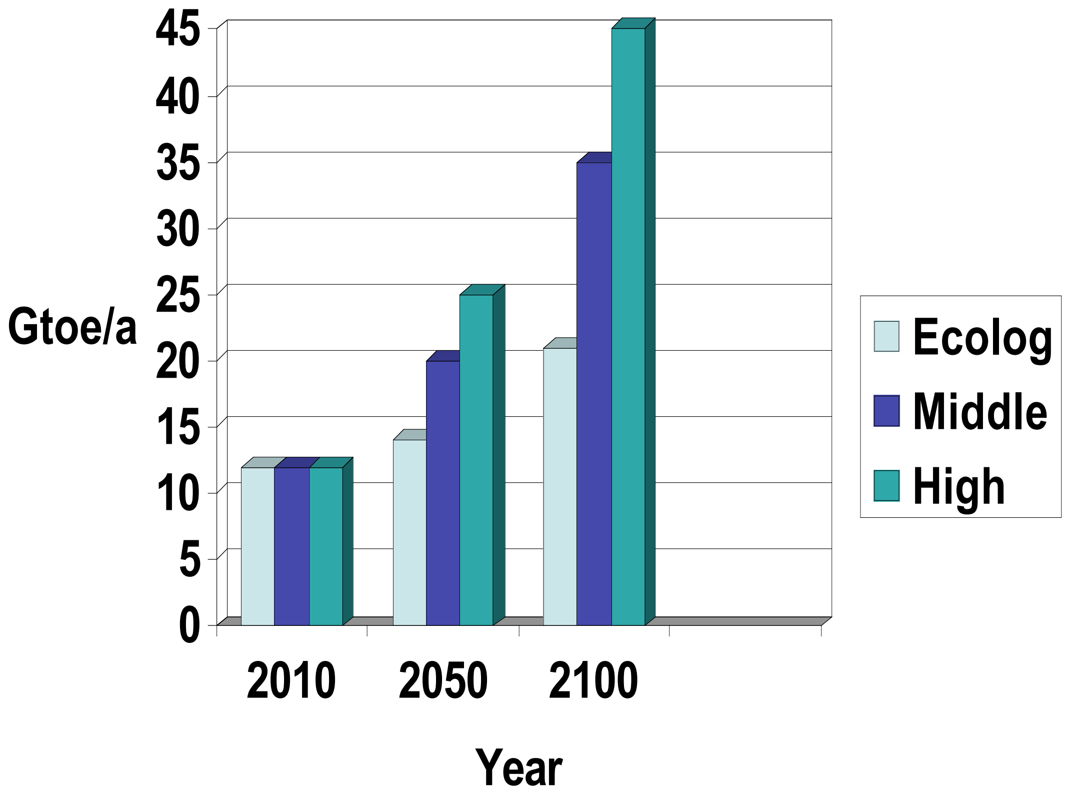
"Path to a direct-drive ignition facility for fusion energy…," Steve Obenschain, HAPL Workshop, LLNL, June 20-21, 2005.

"The Fast Track to Fusion Power The Fast Track to Fusion Power," Chris Llewellyn Smith, IAEA 2005.

"Energy: Science, Policy, and the Pursuit of Sustainability," Bent et al editors, Island Press 2002, Chp2 "Future World Energy Needs and Resources," John Sheffield.

Projected World Energy Demand in Gtoe
(Gigatonnes of oil energy equivalent per year)

Summary projections of
Holdren,
IIASA/WEC
MITRE,
Sheffield.



Fossil Energy in Gtoe/a

WEC 1995 & 2004

Type	Annual Use Gtoe/a	Recoverable	Additional (%?)	Speculative
COAL	3.10	643	968	2900
OIL + NGLs	3.50	148	Conventional	
OIL Unconv.	0.22	% of 1118	Shale Oil, Bitumen and Heavy Oil	
GAS	2.23	146	Methane Hydrates	3000 - 18800
TOTAL	**9.05**	**937 + %1118**	**968**	5900 - 21700

Note proved recoverable: Coal: **567** (1995) and **643** (2004).
Oil: **141** (1995) and **148** (2004).
Gas: **121** (1995) and **146** (2004).

Renewable Energy Resource Base in Gtoe per year

Resource	Current Use [a]	Technical Potential
Hydropower	0.23 el	1.3
Biomass Energy	1.19 th	> 6.6
Solar Energy	0.002 th	> 37.5
Wind Energy	0.005 el	15.2
Geothermal En.	0.014 el +th	(119)[b]
Ocean energy	n.e.	n.e.
TOTAL	**1.44**	**> 60**

(a) Present world energy use is about **11** Gtoe per year
(b) Stored energy in Gtoe. Annual recovery will be less than solar.
n.e. Not estimated
The electricity part may be converted to equivalent primary energy with an average factor of 2.6x.

Nuclear Energy Resources

- The WEC 2004 estimates ~ 13 Mt of uranium recoverable at < $130/kgU.
- In conventional reactors equals 130 Gtoe.
- With breeder reactors equals 6,500 Gtoe.
- Annual consumption is around 0.6 Gtoe.
- With breeders, higher fuel costs should be acceptable. Uranium from seawater?
- In addition there is thorium

So. What is the Problem?

- There are enormous untapped energy resources - fossil, nuclear, and renewables - but they are not uniformly distributed!
- All energy use causes pollution.
- Nuclear proliferation is a concern.
- Financing is an issue.
- These raise substantial geopolitical concerns.
- **Fusion energy will be part of the solution.**

Meeting the Needs of the Developing World

- "My hope is to move beyond the Kyoto debate and to collaborate on new technologies that will enable the United States and other countries to diversify away from fossil fuels so that the air will be cleaner and that we have the economic and national security that comes from less dependence of foreign sources of oil." President Bush in L.A. Times

- "… the availability of easily moveable, cheap fuel is essential for the developing areas to … stabilize their populations at a sustainable level. In the near term fossil fuels can fulfill this role." John Sheffield in Energy: Science, Policy etc.

- Ergo, in the developed world, we should improve energy efficiency and increase the percentage of renewable and nuclear energies – including deploying fusion as soon as possible!!

Distant Future with No Fossil Fuel Use

- 11 billion people using 2.5 toe/cap.a. => **27.5** Gtoe/a.
- Assuming 2x improvement in efficiency, average ~ 5.0 toe/cap.a today (U.S. use about 8 toe/cap.a)

Example

Renewables 13.5 Gtoe/a
= 0.6 hyd + 2.4 biom + 4.2 wind + 0.3 geoth + 6.0 solar.

Nuclear **14.0** Gtoe/a (equivalent raw energy?)
= 7.0 fission + 7.0 fusion
~ 5800 GWe + 5800 GWe

Fast Track to Fusion

- A FESAC report describes how fusion energy might be developed in 35 years. It would be possible to go faster than this plan – see European and Japanese plans.

- There are good opportunities for accelerating Fusion Energy –based on successes in both Inertial and Magnetic Fusion

Pace of Fusion Deployment

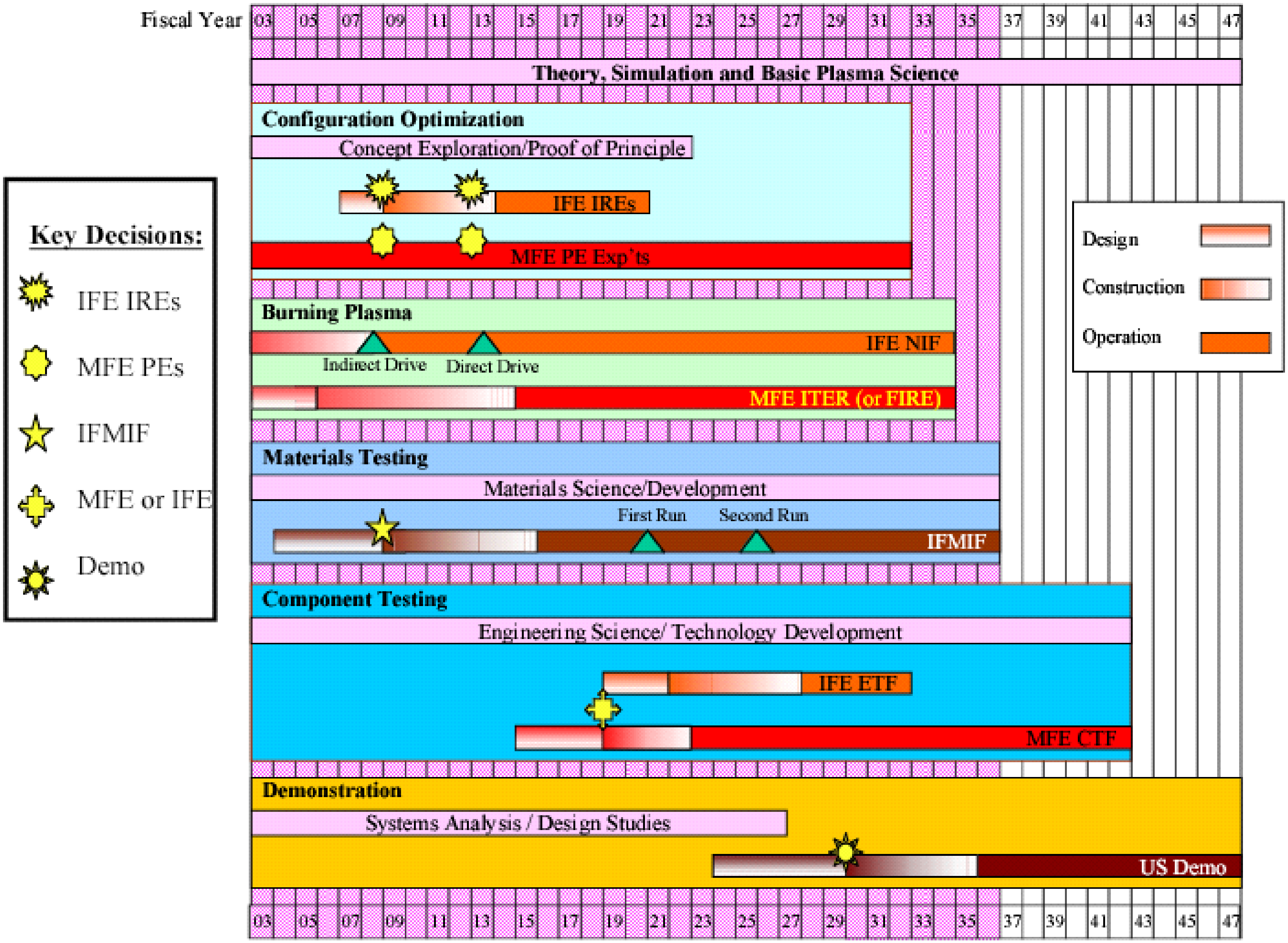
Physics Today, page 27, August 2005, quoted Ray Orbach as saying , “with any kind of luck … Fusion power plants would come on line by 2050… and by the end of the century, 10%-20% of the world’s energy could be produced by fusion.”

Assuming 80% availability and an electrical efficiency of 50%, producing 2.75 to 5.5 Gtoe/a would require 2300 to 4600 GWe of fusion power to be operating.

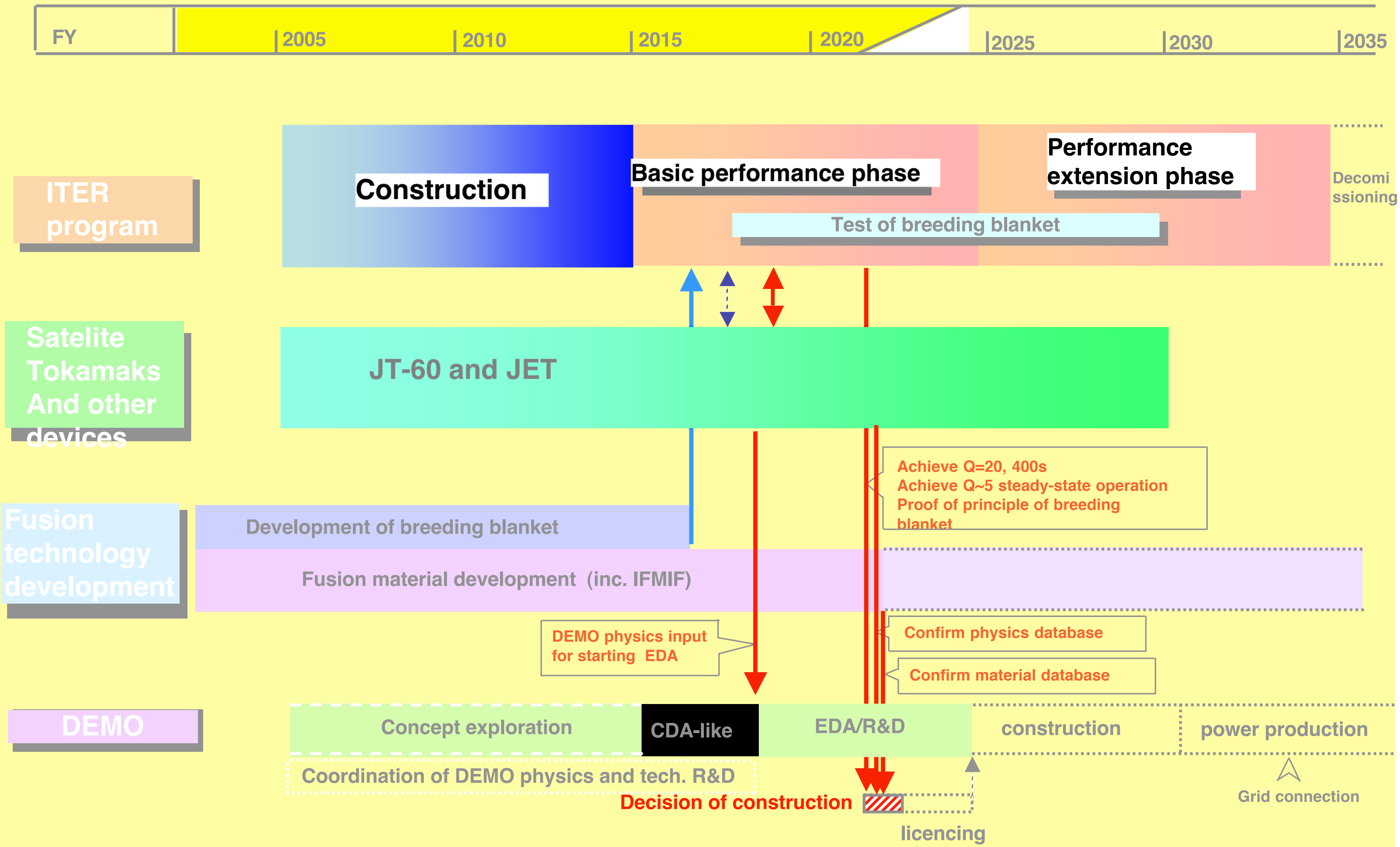
The fastest rate at which fusion plants can be constructed, with tritium available and producing net energy, is about 5 years

Easier to achieve goals if first plants were operating earlier, say 2040-2045 and there was more time to debug them.

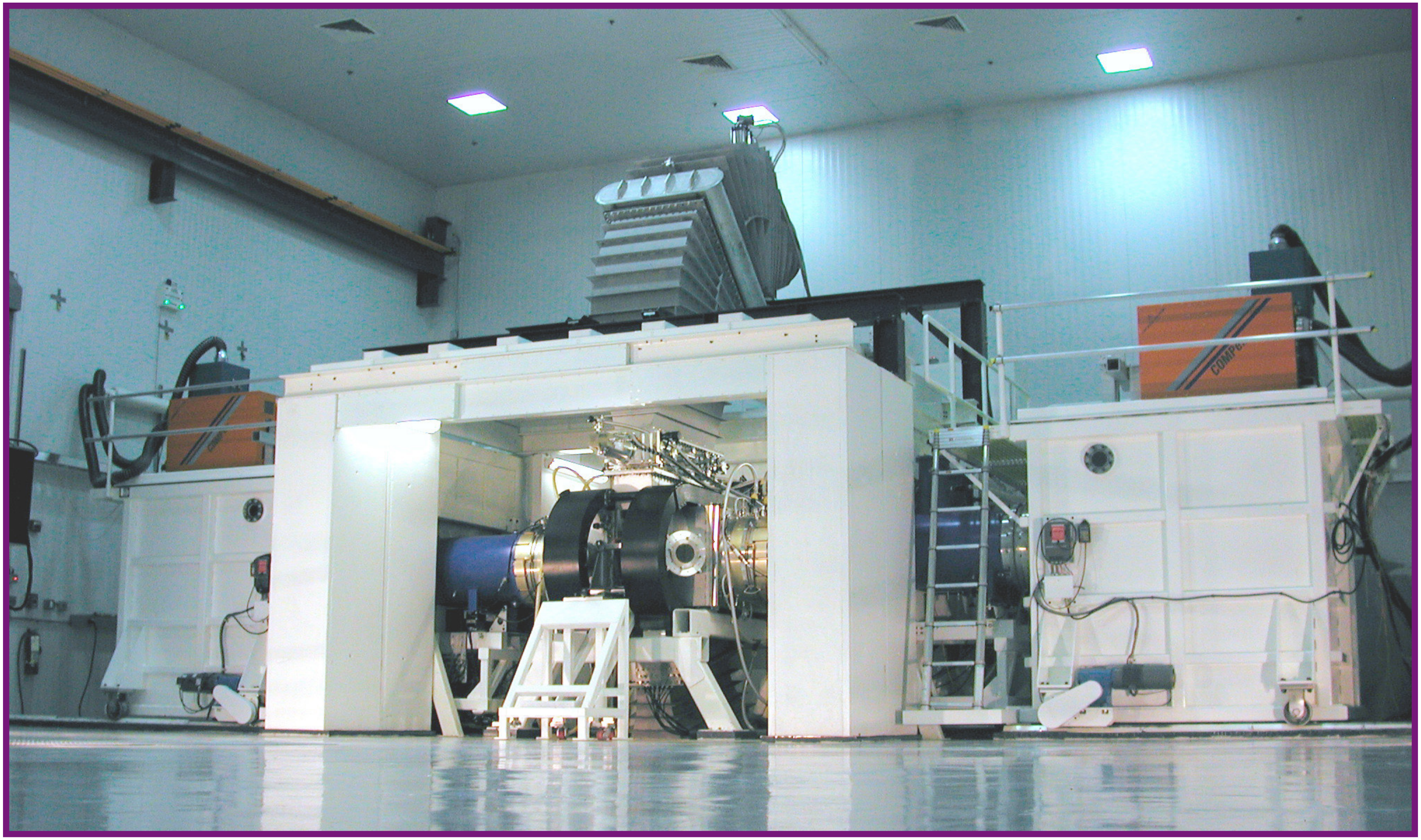
FESAC/DOE 35 Year Plan for Developing Fusion Energy



2. JA / EU roadmap to Fusion DEMO



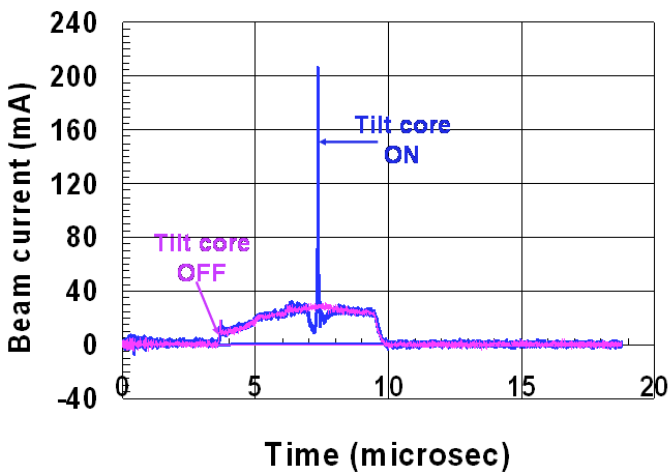
Electra's main amplifier



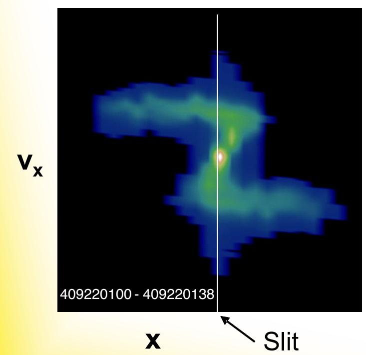
Two-sided e-beam pumping: 500 kV, 100 kA, 140 ns FWHM

Since the last PAC: spectacular progress towards HEDP and Fusion!

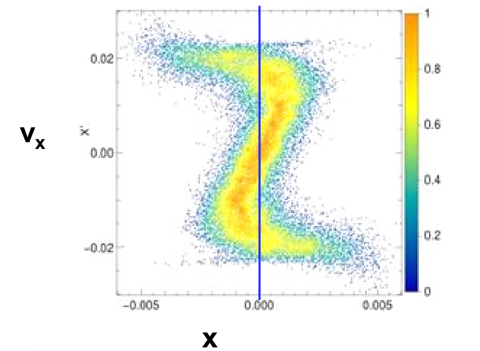
<u>Unique ion pulse compression in plasma</u>: from concept to simulation to 50X compression data in 12 months



<u>Measured</u> v_x vs x.

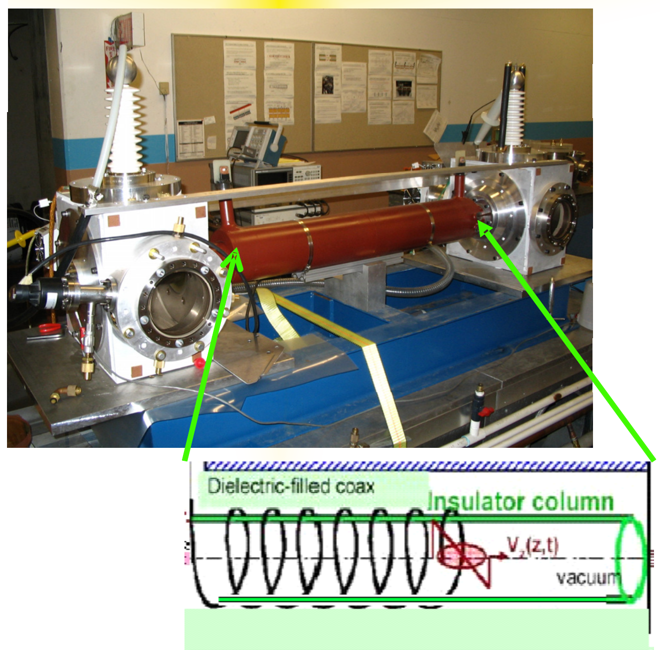


3-D <u>simulation</u> of electron cloud affecting ion beam v_x vs x



<u>Unique world class capability in electron cloud physics</u>: from transport data in four HCX quads to self-consistent simulation in 9 months

<u>Unique accelerator concept</u> (PLIA): from Oct workshop to simulation to initial tests in 8 months



Z-Pinch Inertial Fusion energy

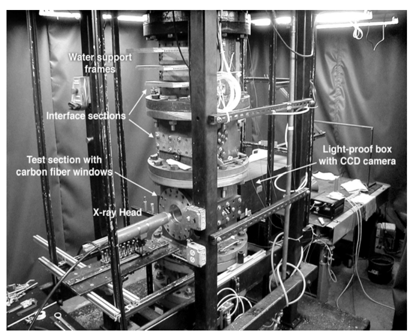
Goal: Develop an economically-attractive power plant using high-yield z-pinch driven targets (~3 GJ) at low rep-rate (~ 0.1 Hz) with recyclable transmission lines (RTLs)

Recent results:

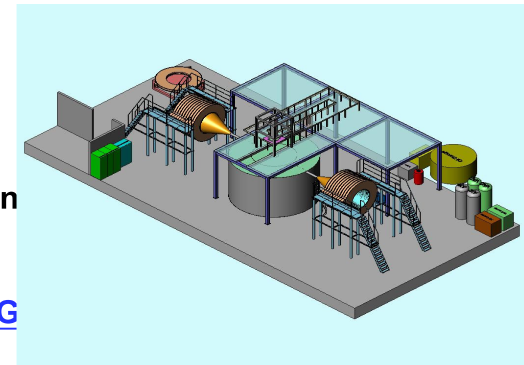
1. RTLs
   simulations (5 MA/cm works)
   experiments (5 MA/cm works)
   pressure testing (20 Torr works)

2. LTD repetitive driver
   0.5 MA, 100 kV cavity fires every 30 seconds
   1.0 MA, 100 kV cavity tested
   full IFE driver architectures

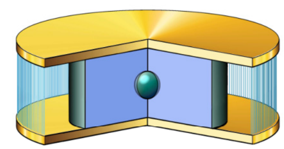
3. Shock mitigation
   theory
   experiments
   simulations



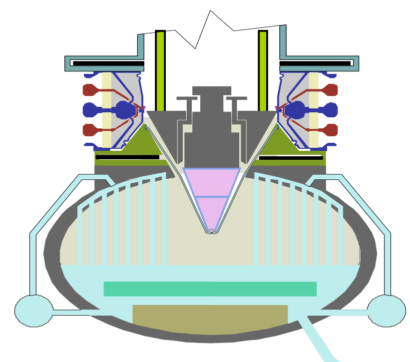
4. Z-PoP planning
   vacuum/electrical connections
   overhead automation
   animations/costing



5. Z-IFE targets for 3 G
   gains ~ 50-100
   double-pinch/dynamic hohlraum
   scaling studies

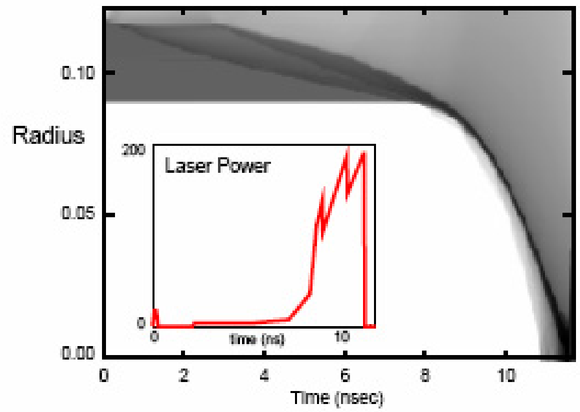


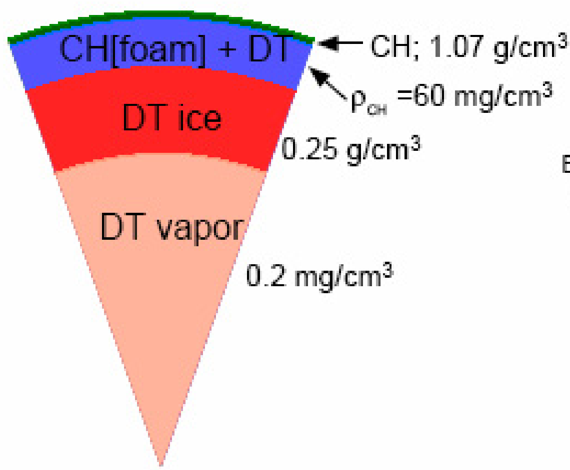
6. Z-IFE power Plant
   RTL manufacturing/costing
   wall activation studies:
   30-40 year lifetime
   power plant design

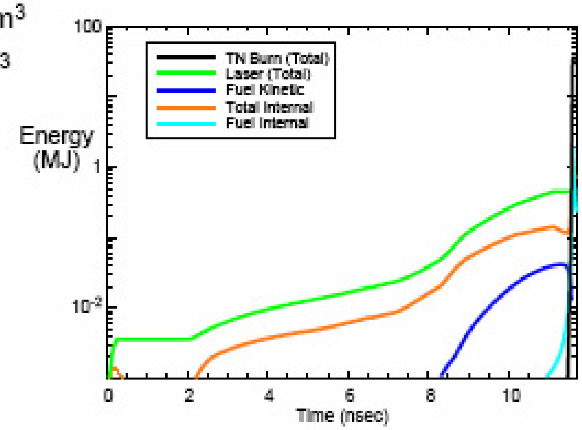


Low Energy KrF-driven target produces gain with high laser intensity and implosion velocity

460 KrF Pellet Design	
Laser Energy	460 kJ
Max Laser Intensity	2.4×10^{15} W/cm^2
Laser Power (peak)	440 TW
Absorption fraction	0.91
Hydro Efficiency	10.2%
Implosion Velocity	4.0×10^{7} cm/s
Peak Fuel ρR	1.9 g/cm^2
Peak IFAR	< 60
Gain	79







New (2005) vision and plan for laser fusion energy

Smaller lower-cost Fusion Test Facility (FTF) based on new pellet designs

Phase I:
1999-2006

Basic laser fusion technology

- Krypton fluoride laser
- Diode-pumped solid-state laser
- Target fabrication and injection
- Chamber materials and optics

Target design & physics

- 2D/3D simulations
- 1-30 kJ laser-target exp.

Phase II
2007-2013

Develop full-size components

- Power-plant laser beamline
- Target fab/injection
- Power plant & FTF design

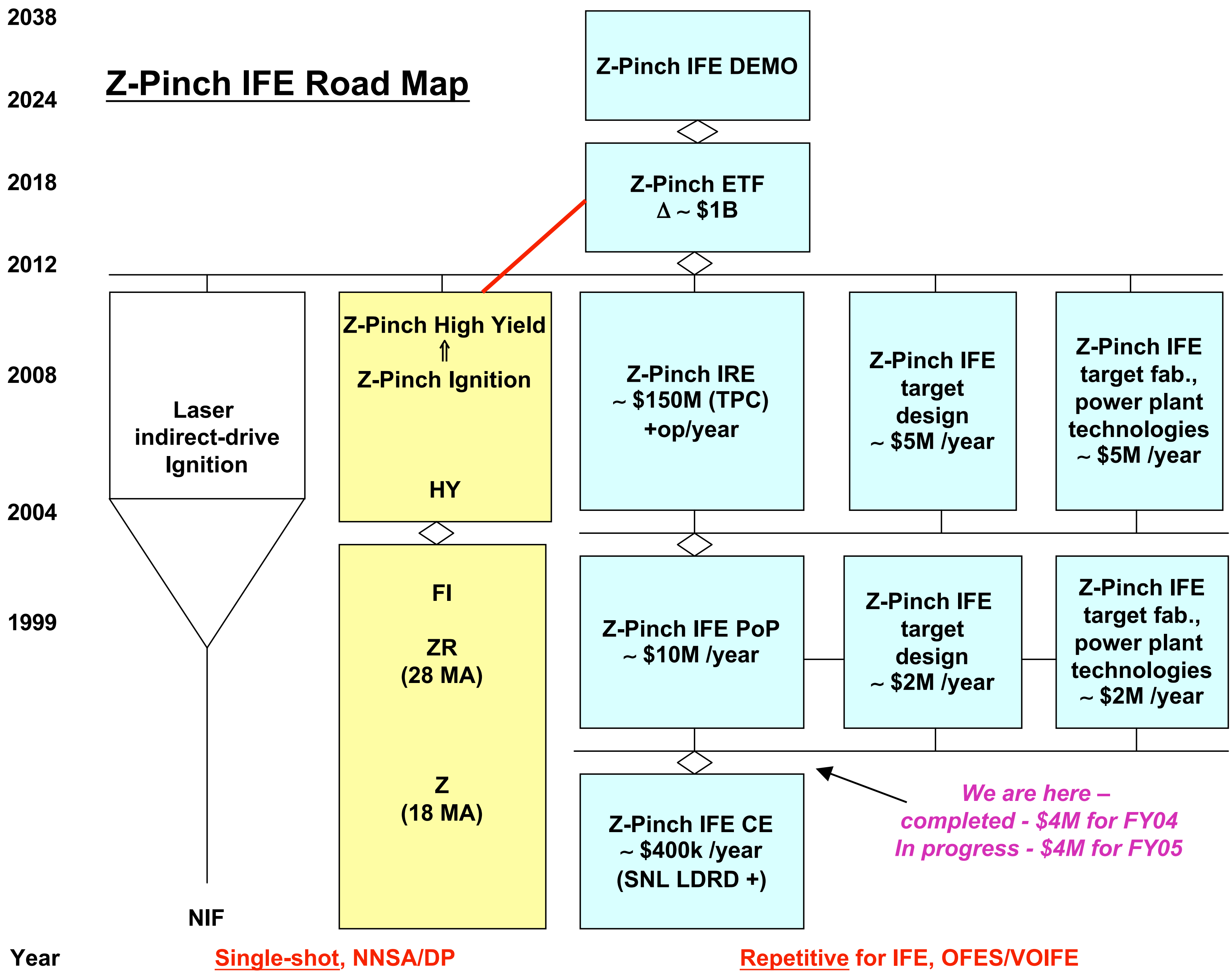
Ignition physics validation

- Calibrated 3D simulations
- LPI experiments

Phase III
FTF operating
~2018

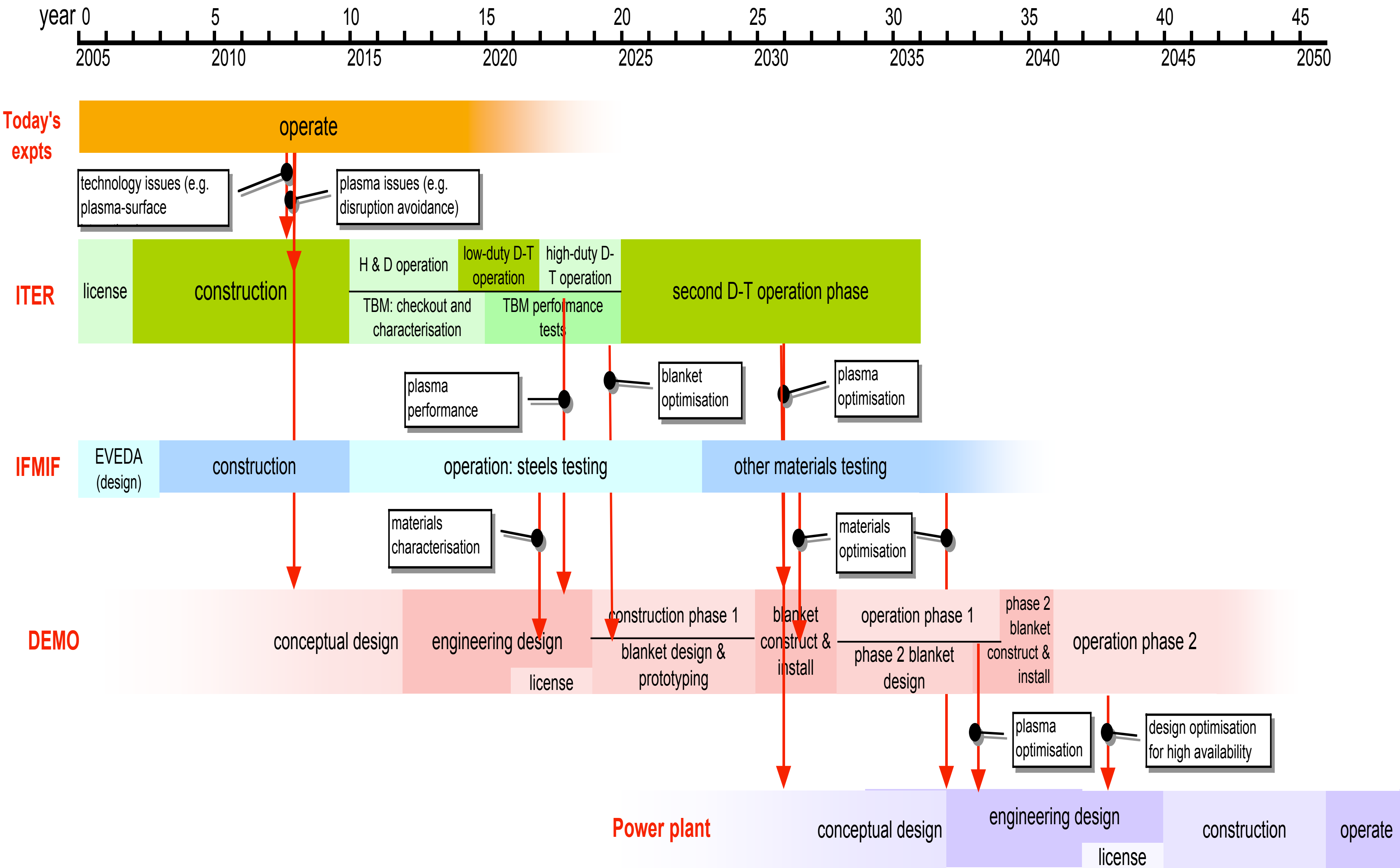
Fusion Test Facility (FTF)

- 0.25 MJ laser-driven implosions @ 5 Hz
- Pellet gains of ~20
- 20-30 MW of fusion thermal power
- Develop chamber materials & components.
- ***Upgrade path to 0.5 MJ and ~150 MW fusion power***



Z-Pinch IFE Road Map
2038
2024
2018
2012
2008
2004
1999
Year
Z-Pinch IFE DEMO
Z-Pinch ETF
Δ ~ $1B
Laser
indirect-drive
Ignition
NIF
Z-Pinch High Yield
⇑
Z-Pinch Ignition
HY
FI
ZR
(28 MA)
Z
(18 MA)
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 +)
We are here –
completed - $4M for FY04
In progress - $4M for FY05
Single-shot, NNSA/DP
Repetitive for IFE, OFES/VOIFE

EU Fast Track Strategy



C. Lewellyn Smith IAEA 2004

SOL characterization, power deposition-width scaling

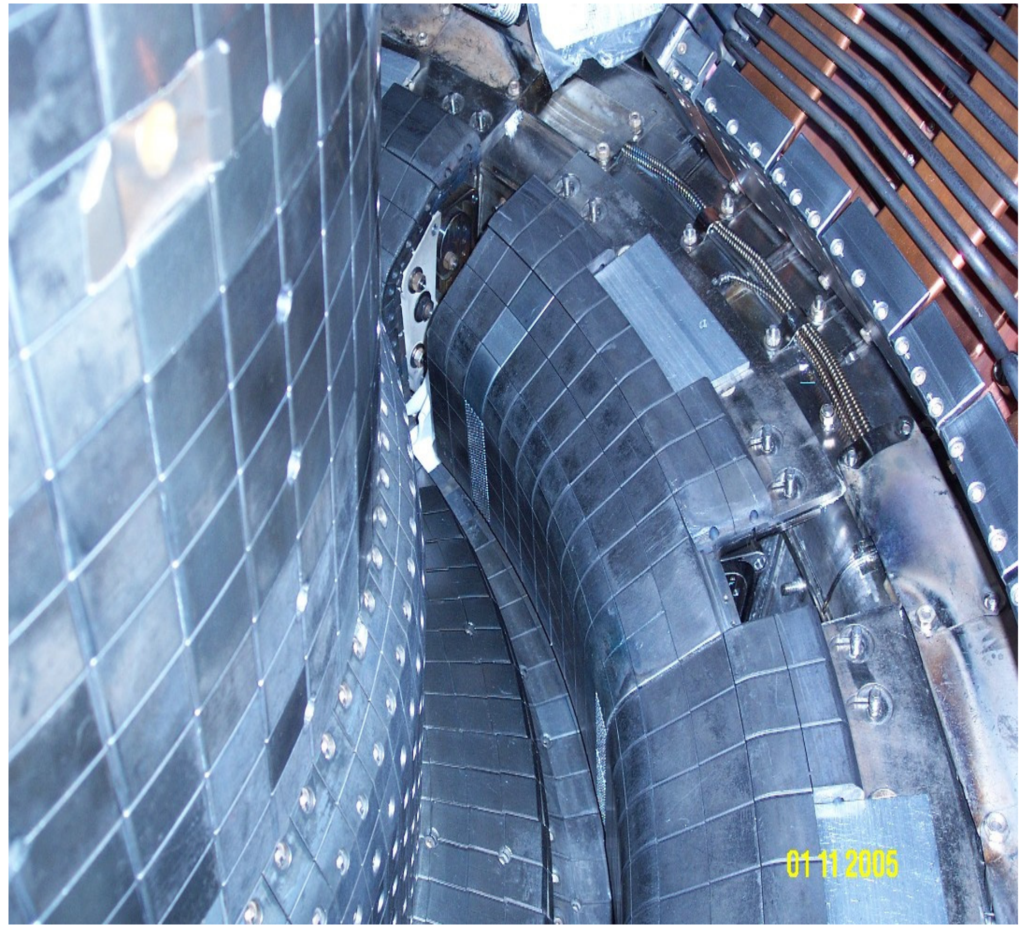
Metallic high-Z first wall with reactor like power loading

Co-deposition/hydrogen Retention

Low ZEFF operation

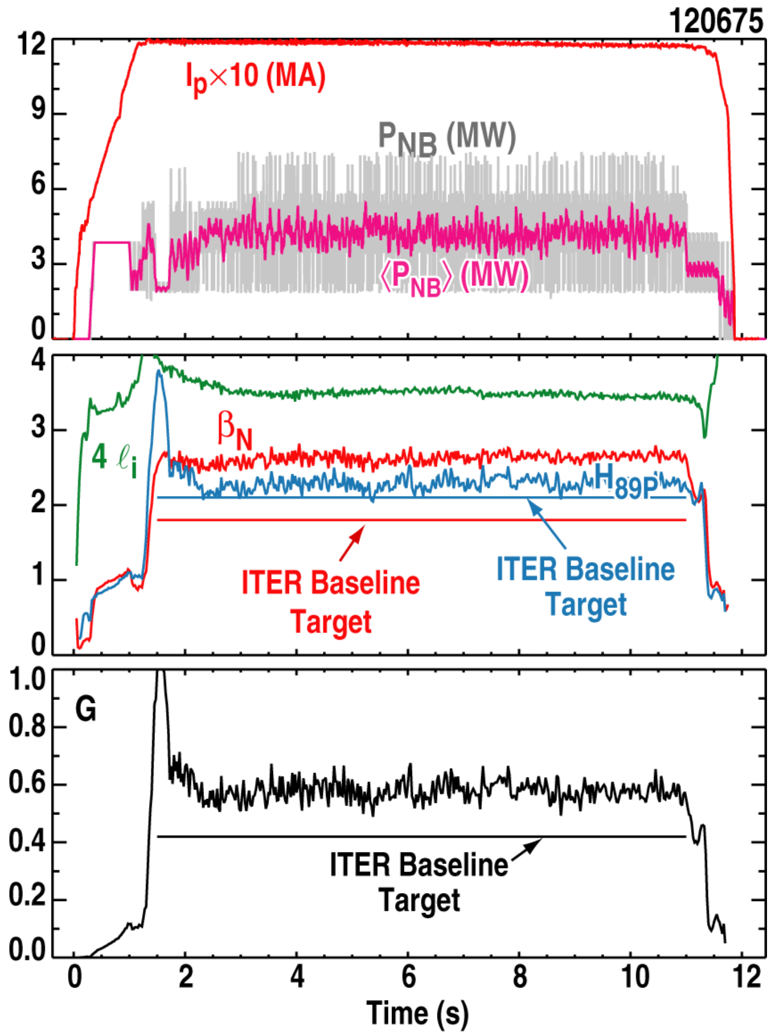
ELM/Disruption survivability
Neutral physics, penetration effects on SOL, pedestal

Lya photon trapping effects on detachment



C-Mod Molybdenum Divertor, with Tungsten Test Tiles

Projections of Advanced Inductive Scenario Indicate the Possibility of Fusion Power Enhancement and Ignition in ITER



Projection to ITER

$\beta_N = 2.8$ $q_{95} = 3.2$ $n/n_G = 0.85$

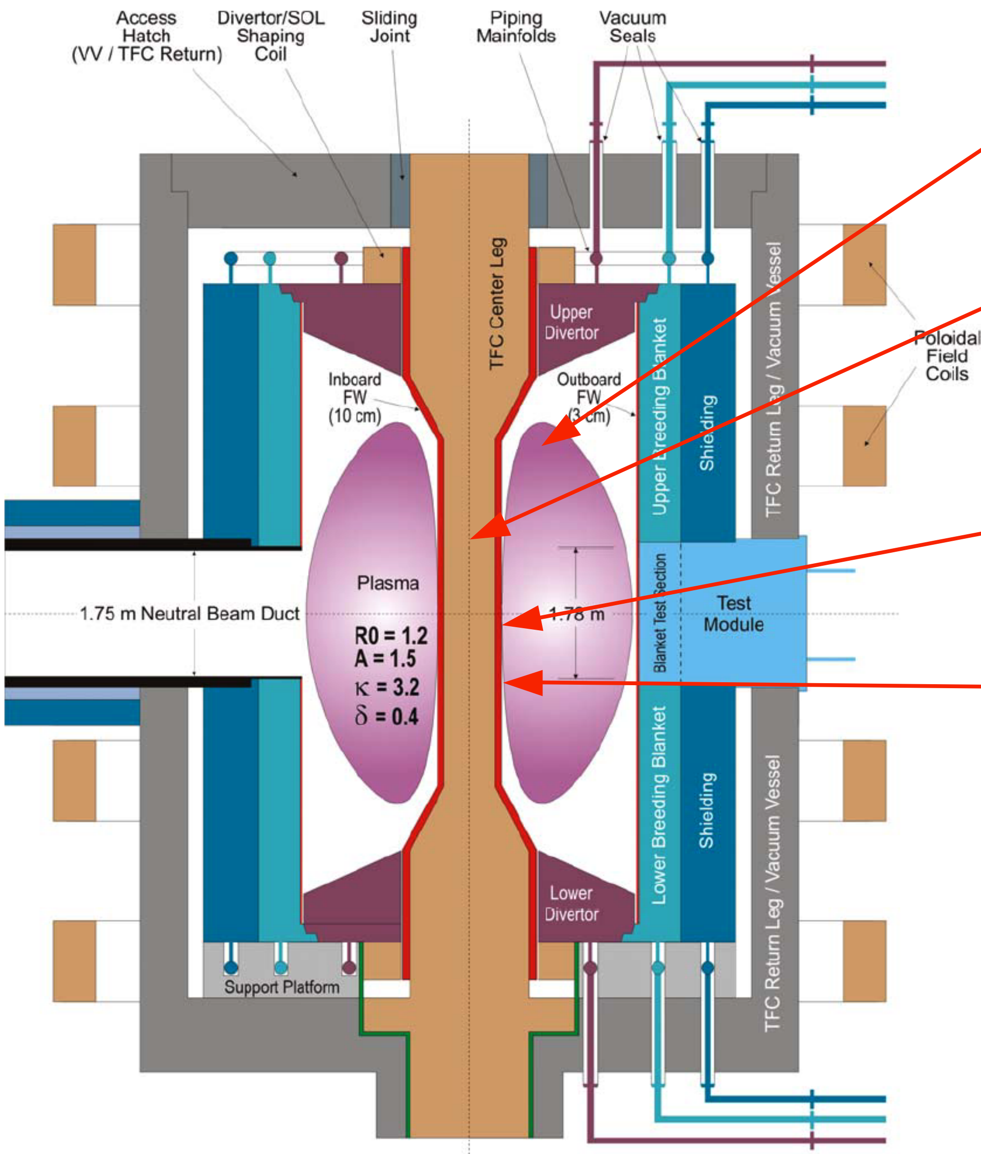
$B = 5.3$ T $I_p = 13.9$ MA

	H	P_{fus} (MW)	P_{aux} (MW)	Q_{fus}
ITER89P	2.4	780	60	12.9
IPB98y2	1.47	740	18.5	39
DS03	1.25 (1.63)*	700	0	∞

*DIII–D Value

Flattop time = 2300 s > 30 min

Unique Properties of ST Combine to Enable Compact, Fully Remote Maintainable CTF



Natural elongation at low ℓ_i → simple shaping coils

I_{TF} ~ I_p; moderate B_T → slender, demountable, single-turn TF center leg

No central solenoid → no inboard nuclear shielding

No inboard blanket → compact device (low R)

~5% fusion neutrons lost to center leg → high tritium breeding ratio

Key Points

- Speed up development of radiation-resistant materials, 14 MeV neutron source, and liquid wall tests.

- Build IFE and MFE component test facilities.