New Trends in Fusion Research

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Credits and acknowledgments

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apologies to the many authors from whom I have ‘stolen’ viewgraphs

Lay-out of the course *(can still be changed!)*

- Mon Oct. 11 –*1h*
  - Fusion basics, Lawson criterion, plasmas, confinement schemes
  - Inertial confinement fusion
- Tue Oct 12 –*2h*
  - Magnetic confinement: principles and general challenges
  - The tokamak
  - Heating and current drive
  - Macroscopic equilibrium, stability, operational limits, disruptions
  - Plasma-wall intereaction
- Wed Oct 13 –*2h*
  - Plasma diagnostics
  - Transport of energy and particles
  - The burning plasma regime
  - The future: ITER, the world burning plasma experiment

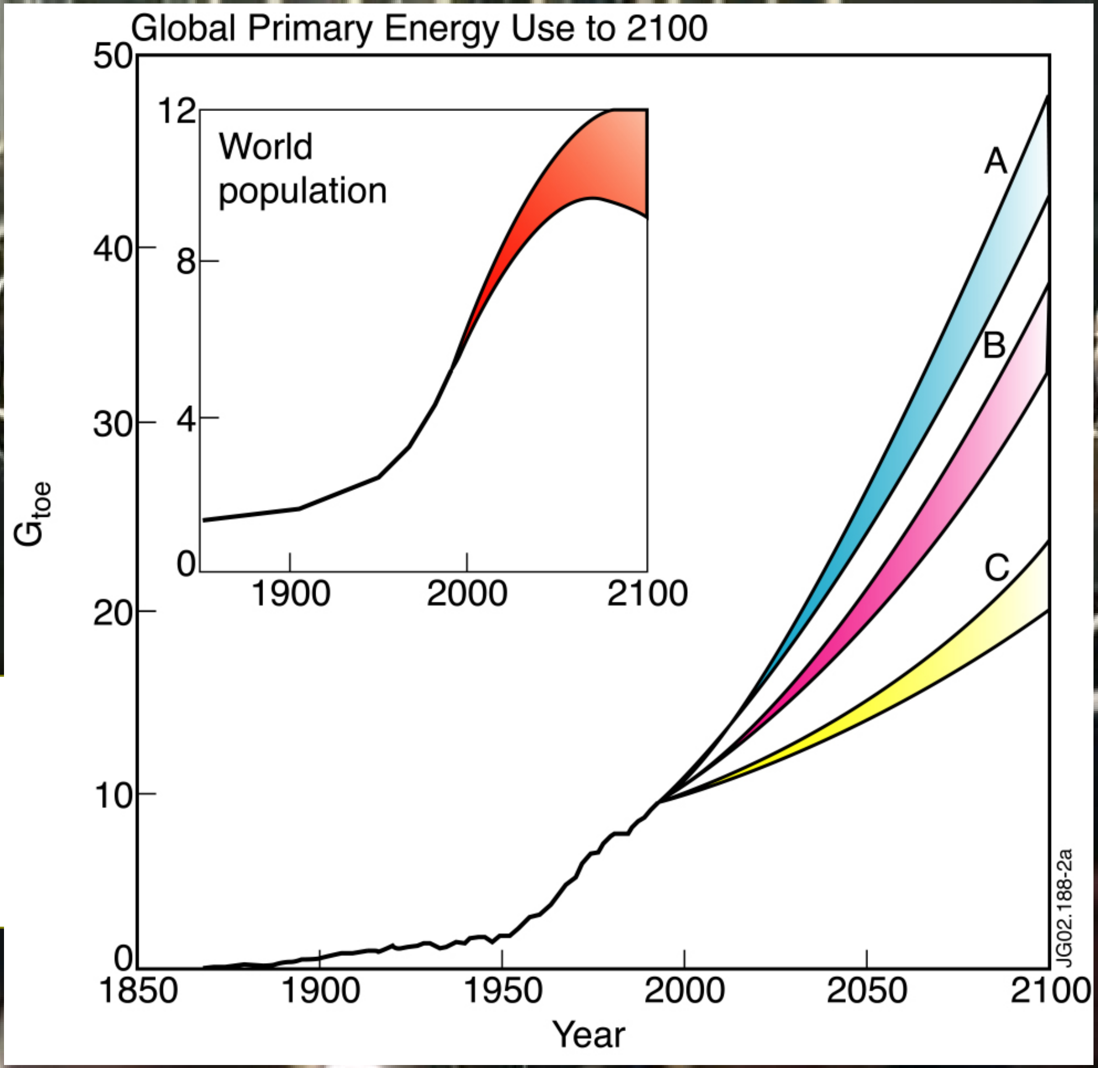
Web links

- Plasma physics lectures at EPFL
  http://crppwww.epfl.ch/lectures/
- CRPP-EPFL http://crppwww.epfl.ch
- EFDA http://www.efda.org
- JET http://www.jet.efda.org
- ITER http://www.iter.org
- A useful US-based site with many fusion links
  http://www.fire.pppl.gov

Lay-out of lecture 1 (today)

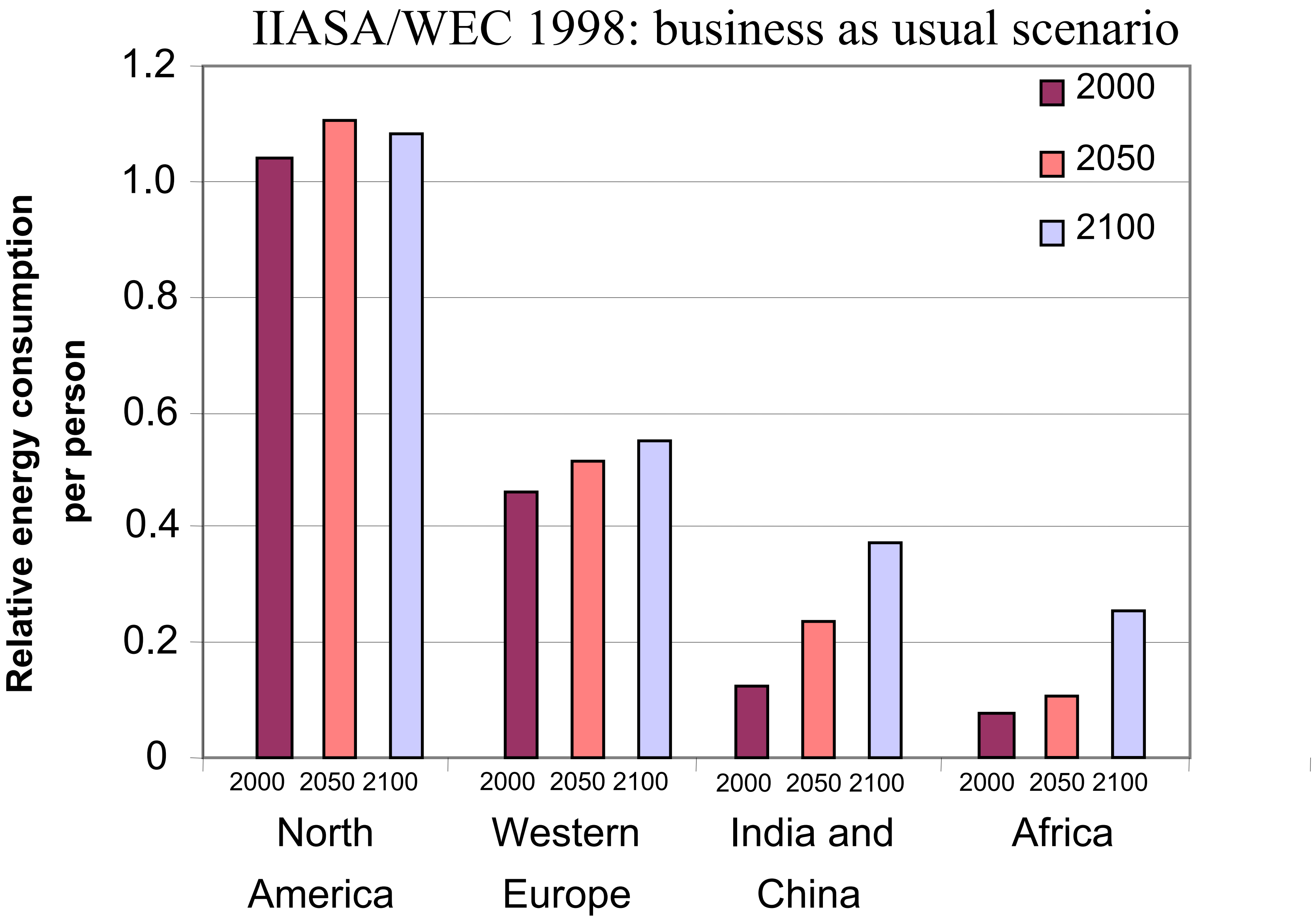
- Fusion basics
  - Energy needs
  - Urgency of alternates to fossil fuels: scarcity, environmental issues
- Plasmas
- Why *thermo*-nuclear fusion? Coulomb collisions in plasmas
- Fusion energy balance: Lawson criterion, breakeven and ignition
- Confinement schemes
- Inertial confinement fusion (*the view of a non-expert*)
  - Direct drive
  - Indirect drive
  - Drivers: lasers, ion beams, X-ray (Z-pinch)
  - Fast ignition

Growth of world population and energy demand



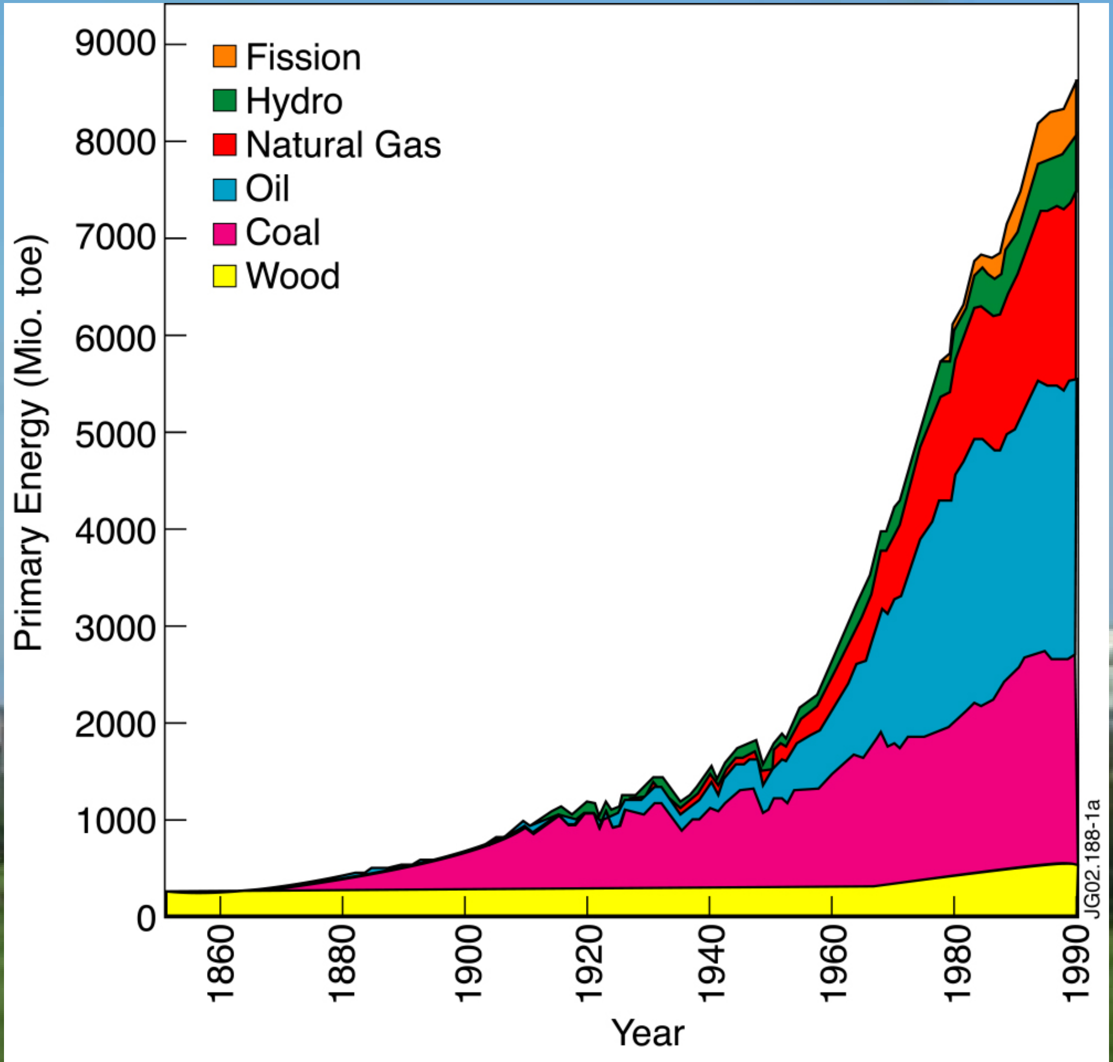
Energy demand grows even faster than world population

Unequal distribution of energy consumption



Reliance on fossil fuels

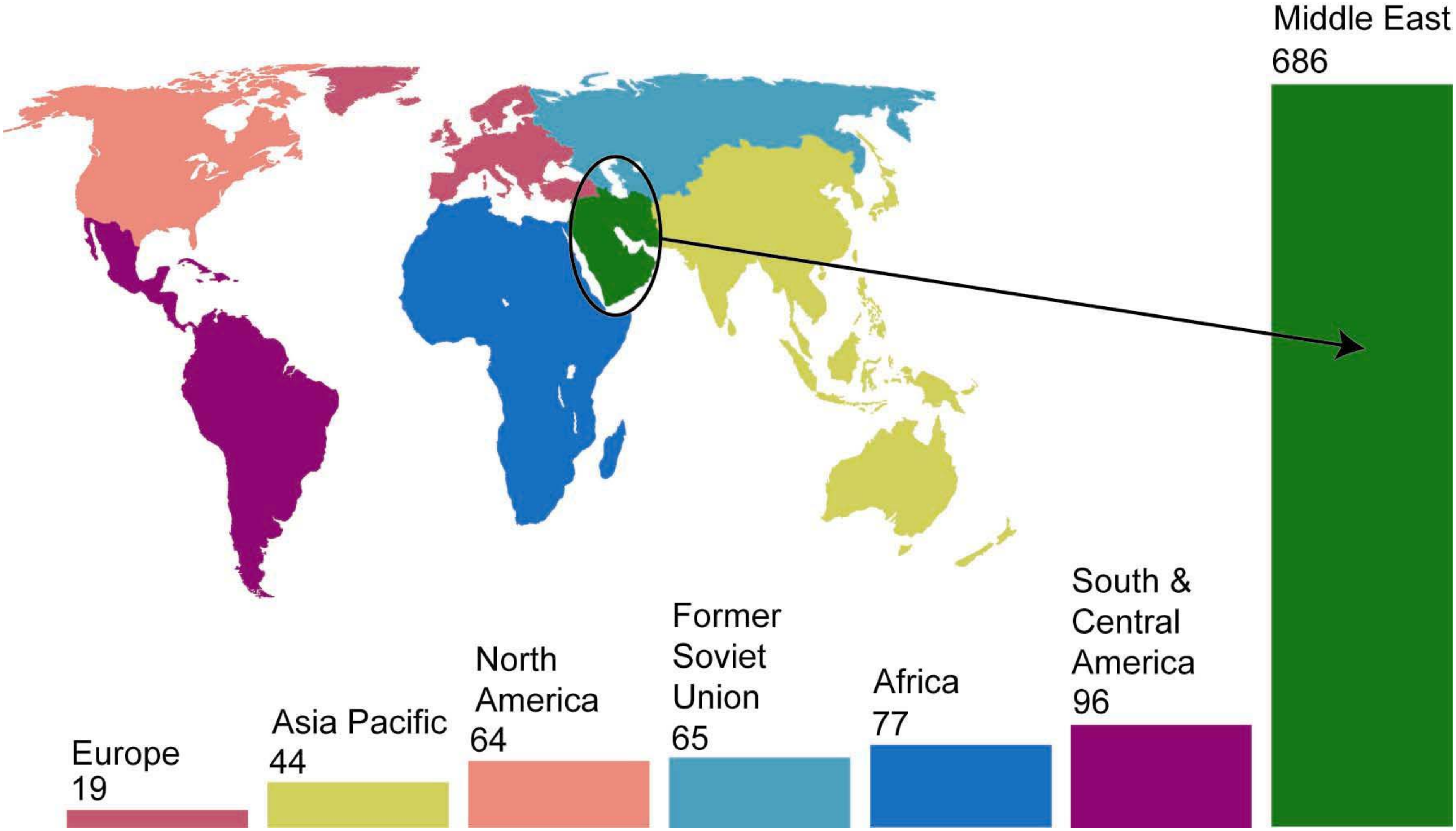
Fossil Fuels have been produced from decayed plant and animal matter over millions of years, cannot be re-formed in time



R.W.Bentley et al., Perspectives on the Future of Oil, Vol. 18, Nos. 2&3 2000, MULTI-SCIENCE PUBLISHING CO. LTD., 107 High Street, Brentwood, Essex, CM14 4RX, UK.

Urgency of alternates development

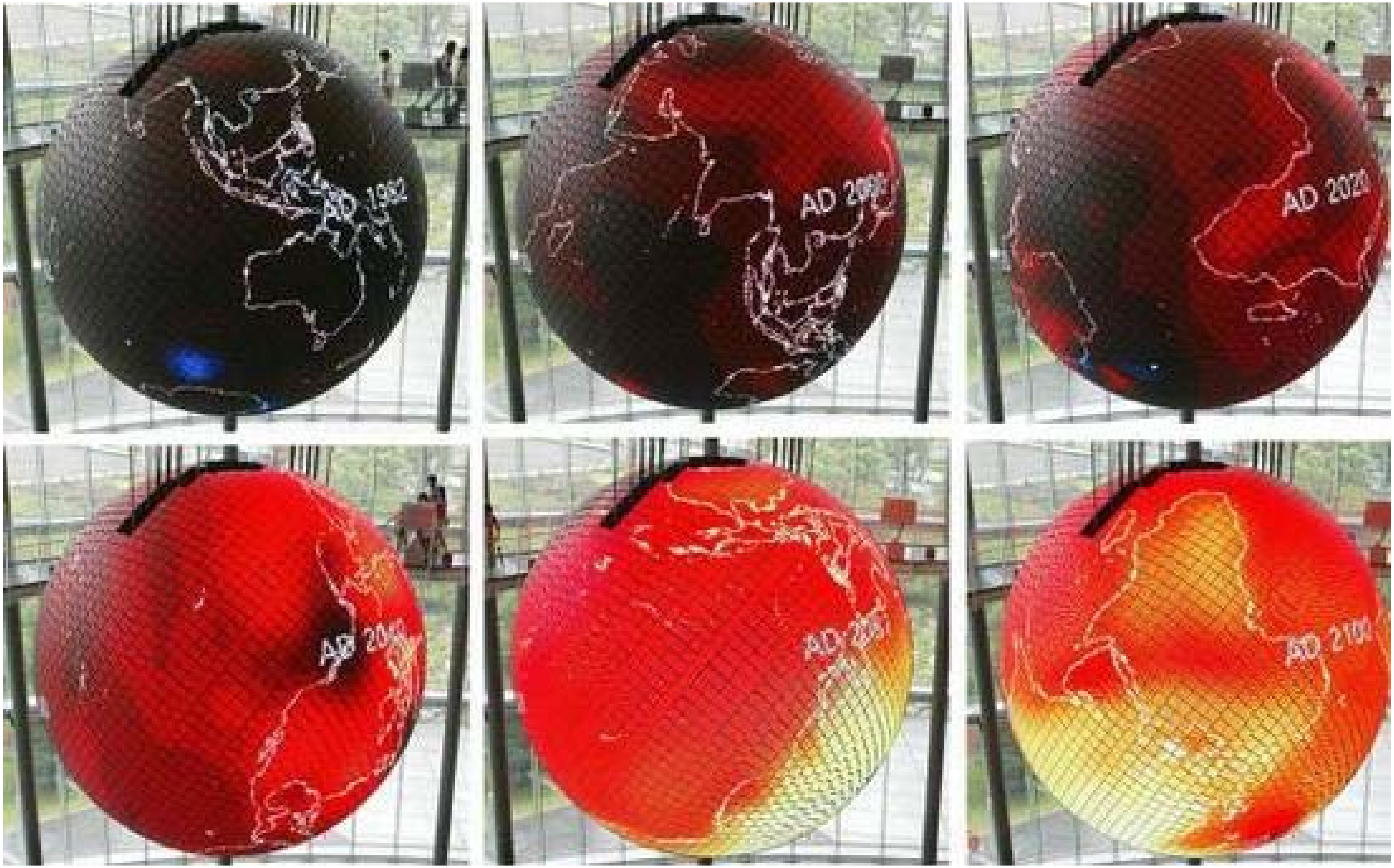
Oil geographical distribution



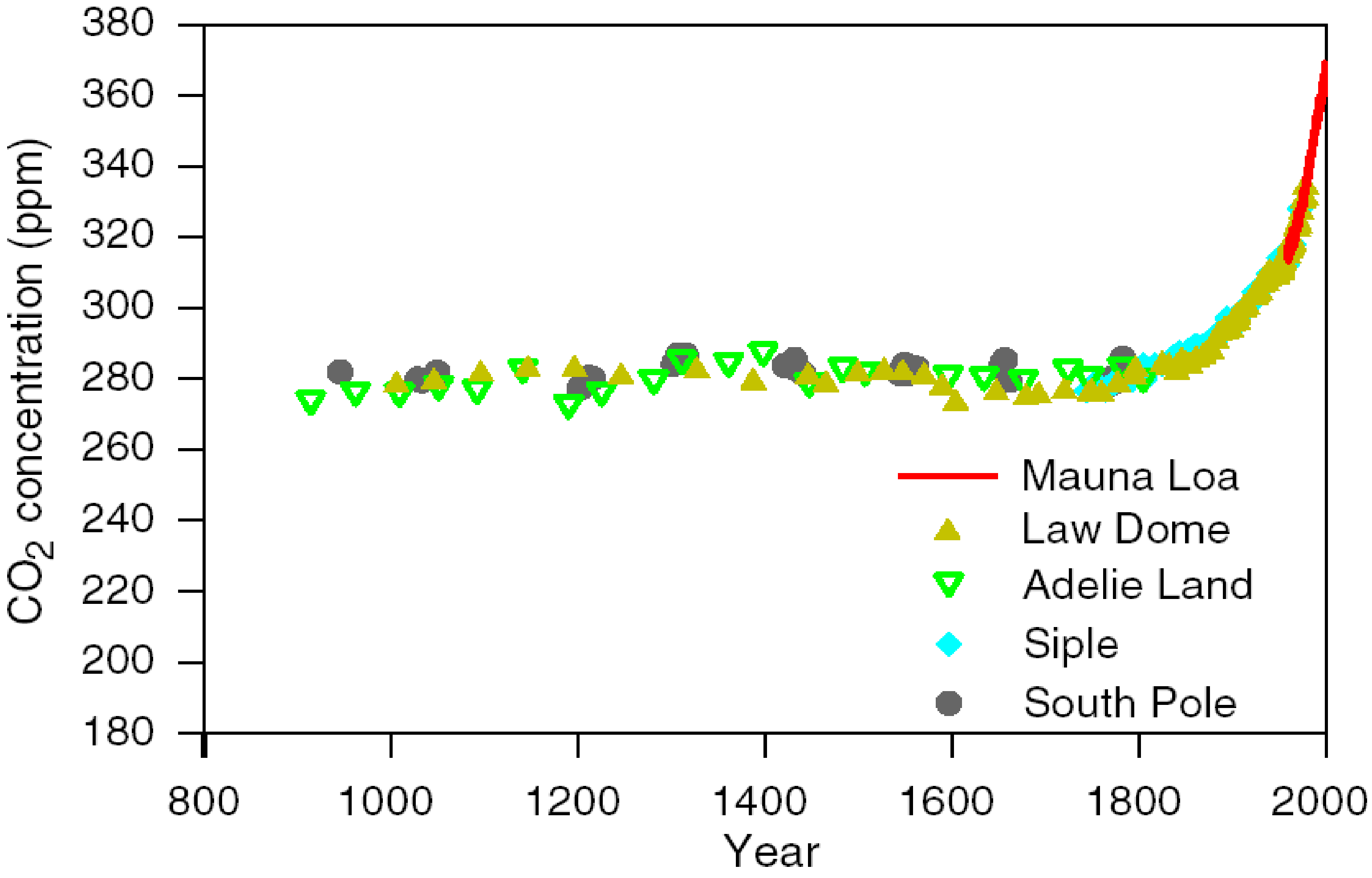
(source BP statistical review 2002)

Urgency of alternates development

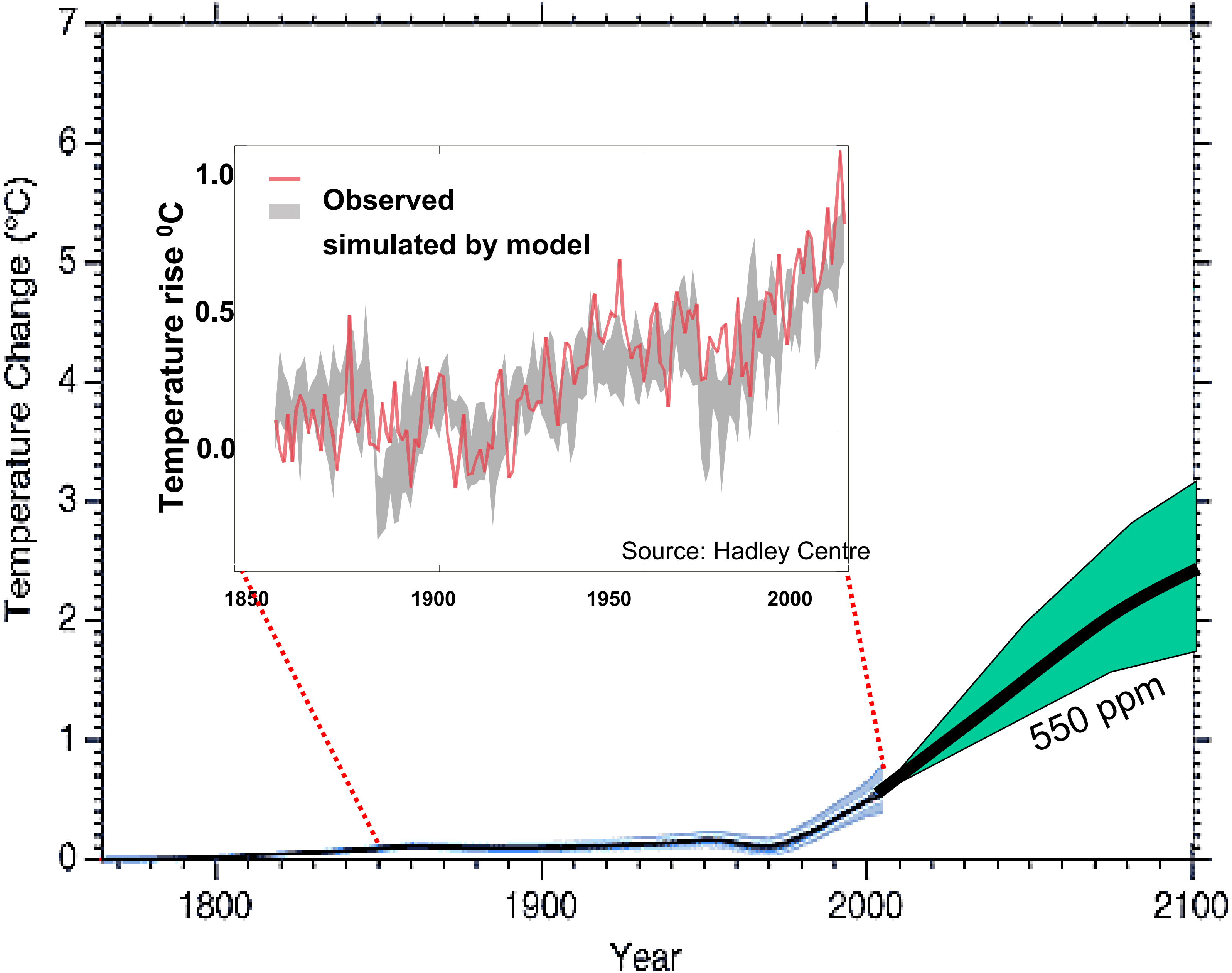
Environmental impact (CO_2 and global warming)



CO_2 is prime greenhouse gas

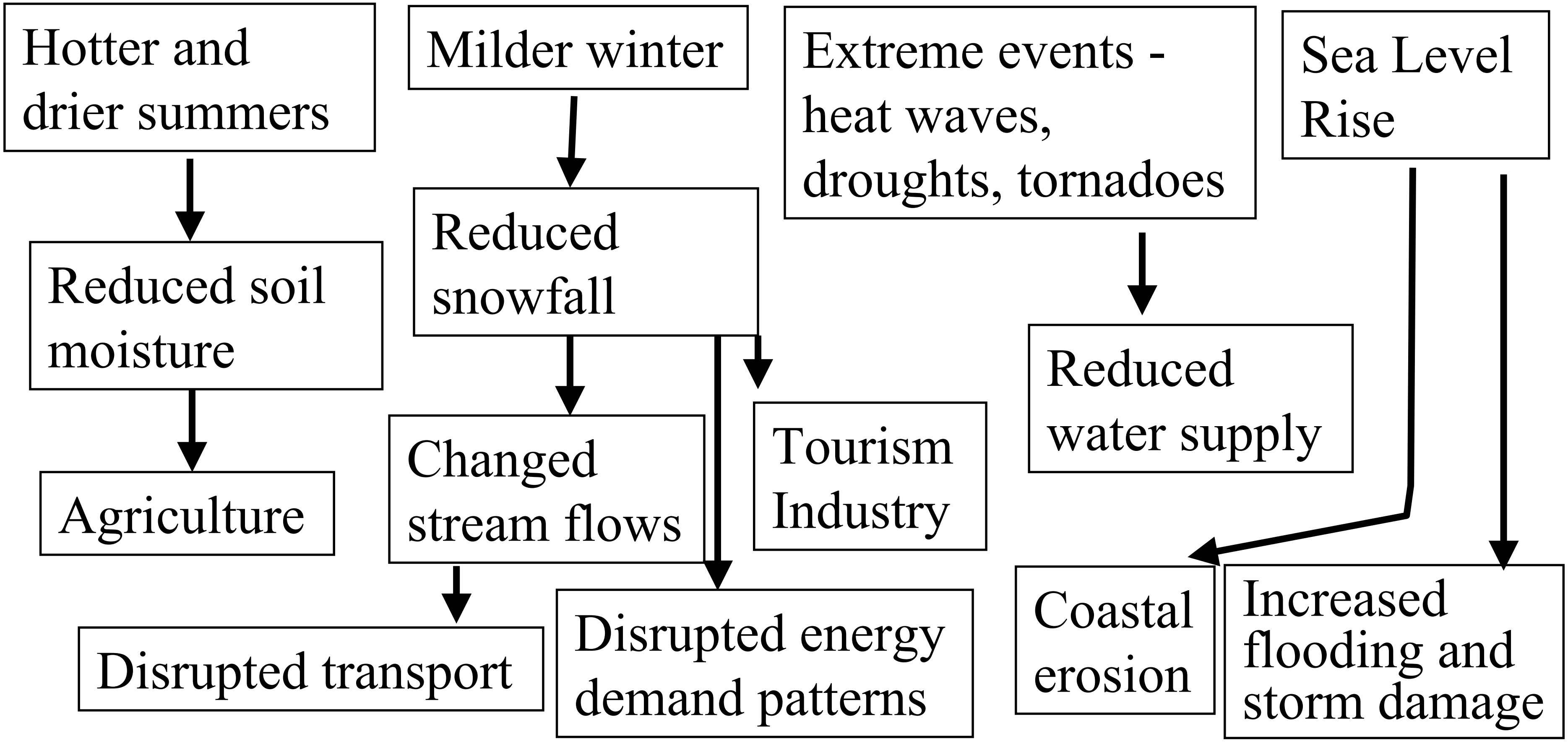


Modelling global warming



Source: Hadley Centre

The effects of climate change



Hotter and drier summers

Reduced soil moisture

Agriculture

Milder winter

Reduced snowfall

Changed stream flows

Disrupted transport

Disrupted energy demand patterns

Tourism Industry

Extreme events - heat waves, droughts, tornadoes

Reduced water supply

Sea Level Rise

Coastal erosion

Increased flooding and storm damage

Ambitious goal for 2050 (when total world power market predicted to be 30TW)

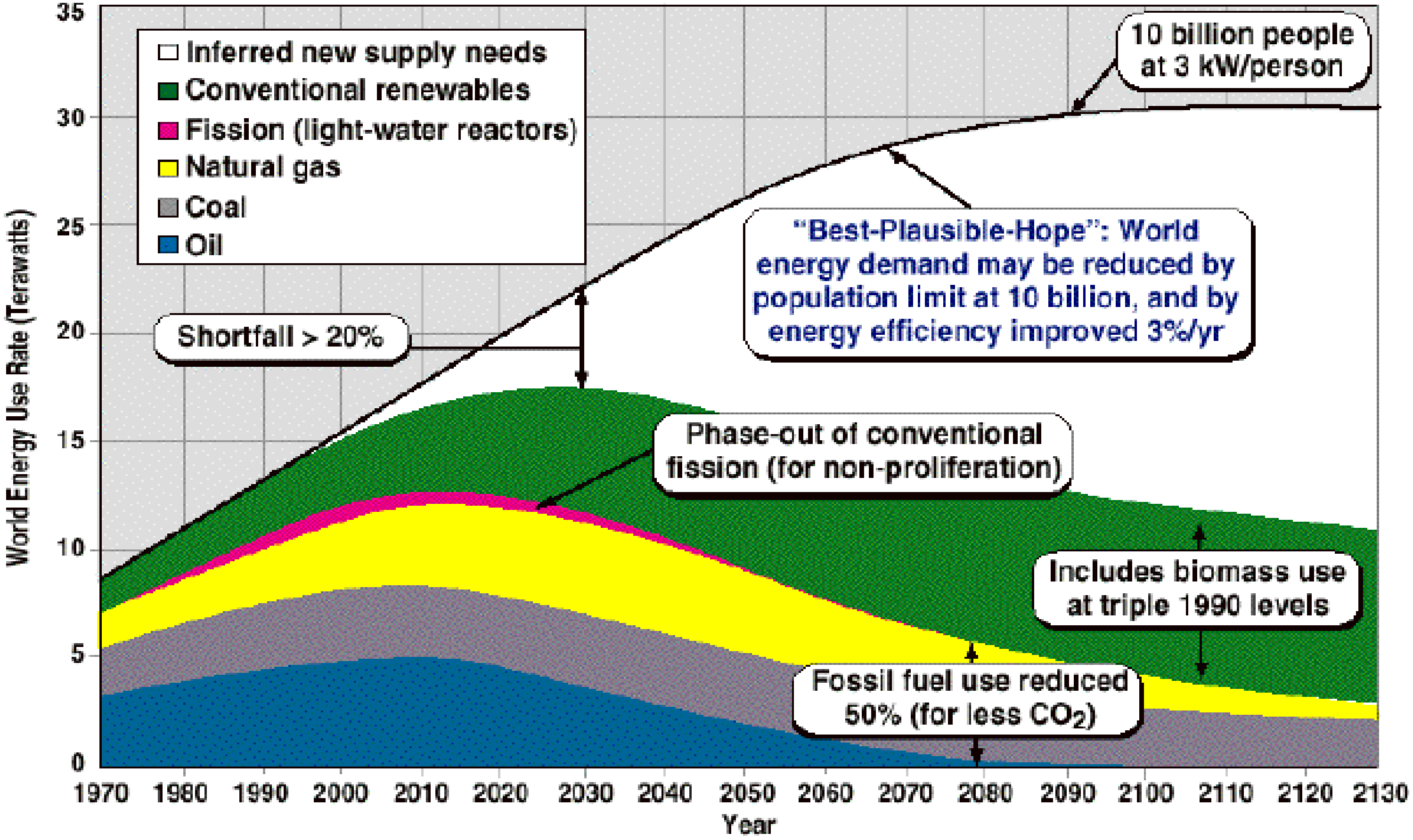
Limit CO_2 to twice pre-industrial level: will need 20 TW of CO_2-free power (today's world total power market is 13 TW)

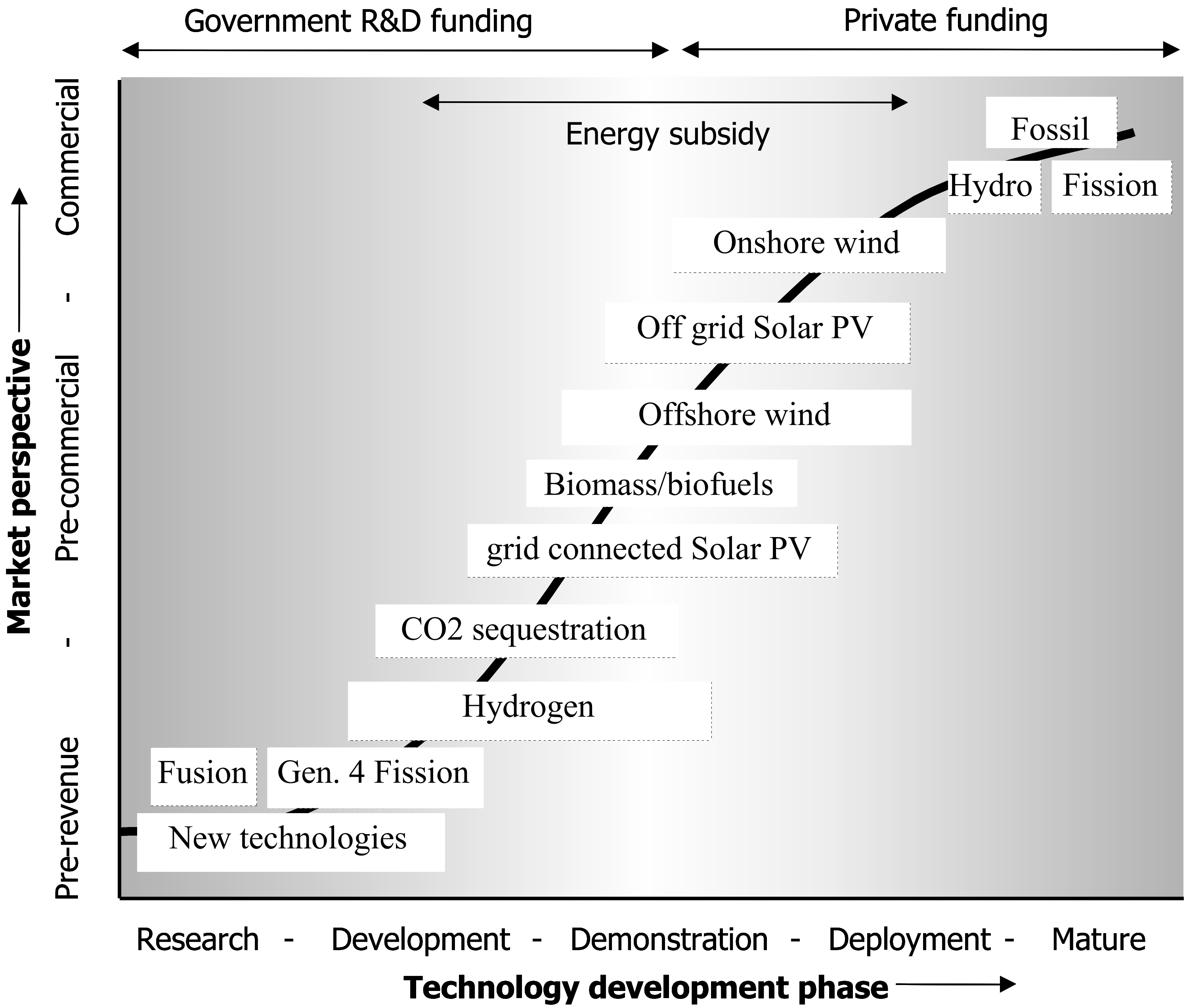
US DoE "The technology to generate this amount of emission-free power does'nt exist"

Urgency of alternates development

Scarcity of resources: related to CO2 limitations

“BEST-PLAUSIBLE-HOPE” PROJECTION: 5 TW OF NEW NON-FOSSIL ENERGY SOURCES NEEDED BY 2030 (e.g., SOLAR, ADVANCED FISSION, FUSION)




Government R&D funding
Private funding
Energy subsidy
Fossil
Hydro
Fission
Onshore wind
Off grid Solar PV
Offshore wind
Biomass/biofuels
grid connected Solar PV
CO2 sequestration
Hydrogen
Fusion
Gen. 4 Fission
New technologies
Market perspective
Pre-revenue - Pre-commercial - Commercial
Research - Development - Demonstration - Deployment - Mature
Technology development phase

Alternative energy sources
Nuclear Fission

- Long lived radioactive waste products (many thousands of years) that require transportation, re-processing and geological storage
- Public concerns on safety

Alternative energy sources
Renewables

Renewables (wind, wave, solar, hydro) are the most attractive option at present and offer long term, clean energy reserves

However :

- Low energy density
- Fluctuations in time require storage systems

Ex.: Contribution to electricity of wind energy in 2002

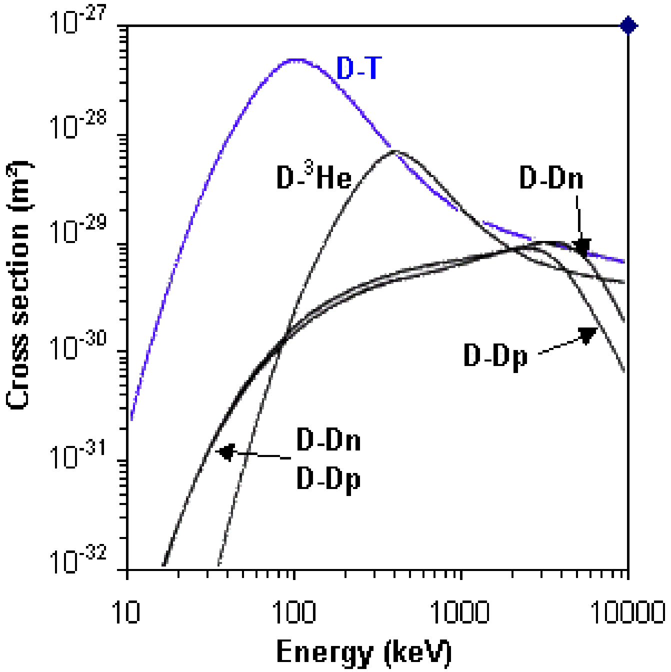
Country or region	Cumul. installed (GW) 2002	share of electricity by wind
Germany	12	4%
Spain	5	5.5%
Denmark	2.8	18.5%
EU	24	2%
US	4.7	0.3%
Total World	32	0.45%

Going to 20% of electricity in EU (240GW) would mean 1500 big wind parks

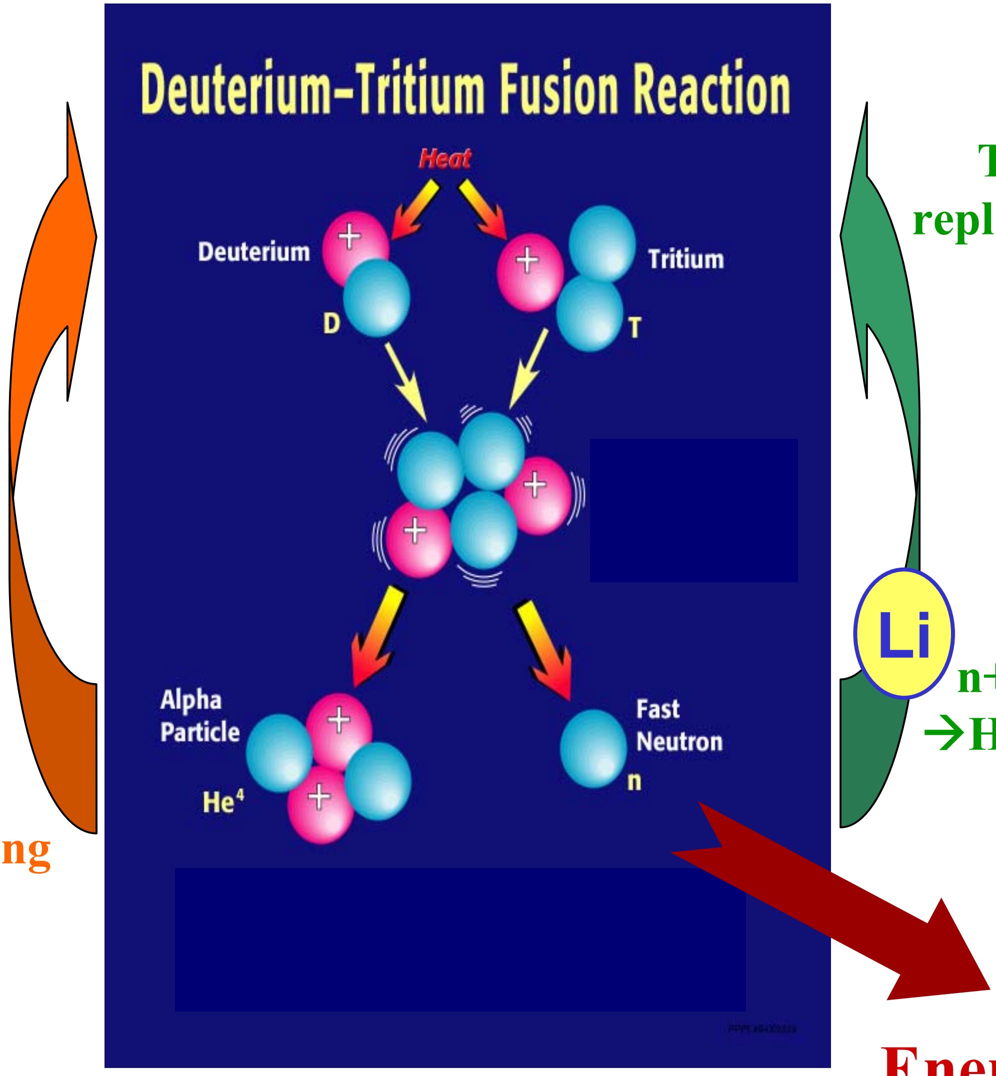
Horns Rev in Denmark: 160 MW (80 mills)

Thermonuclear Fusion

Fusion reactions



$D+T \rightarrow {}^{4}He\,(3.5MeV) + n(14MeV)$



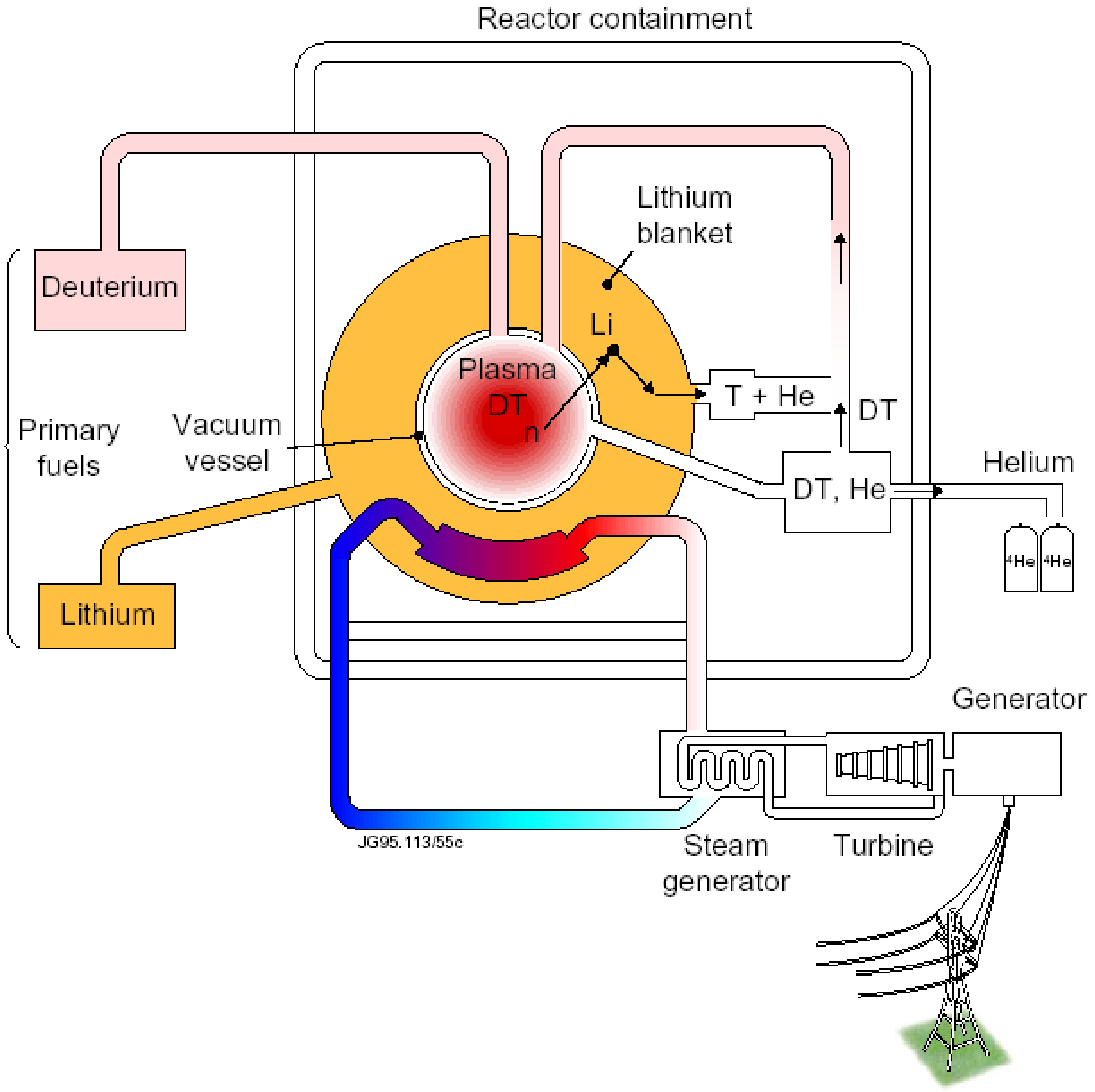
Tritium replenishment

$n+Li^{6(7)} \rightarrow$
$\rightarrow He^{4}+T\ (+n)$

Plasma self-heating

Energy for electricity

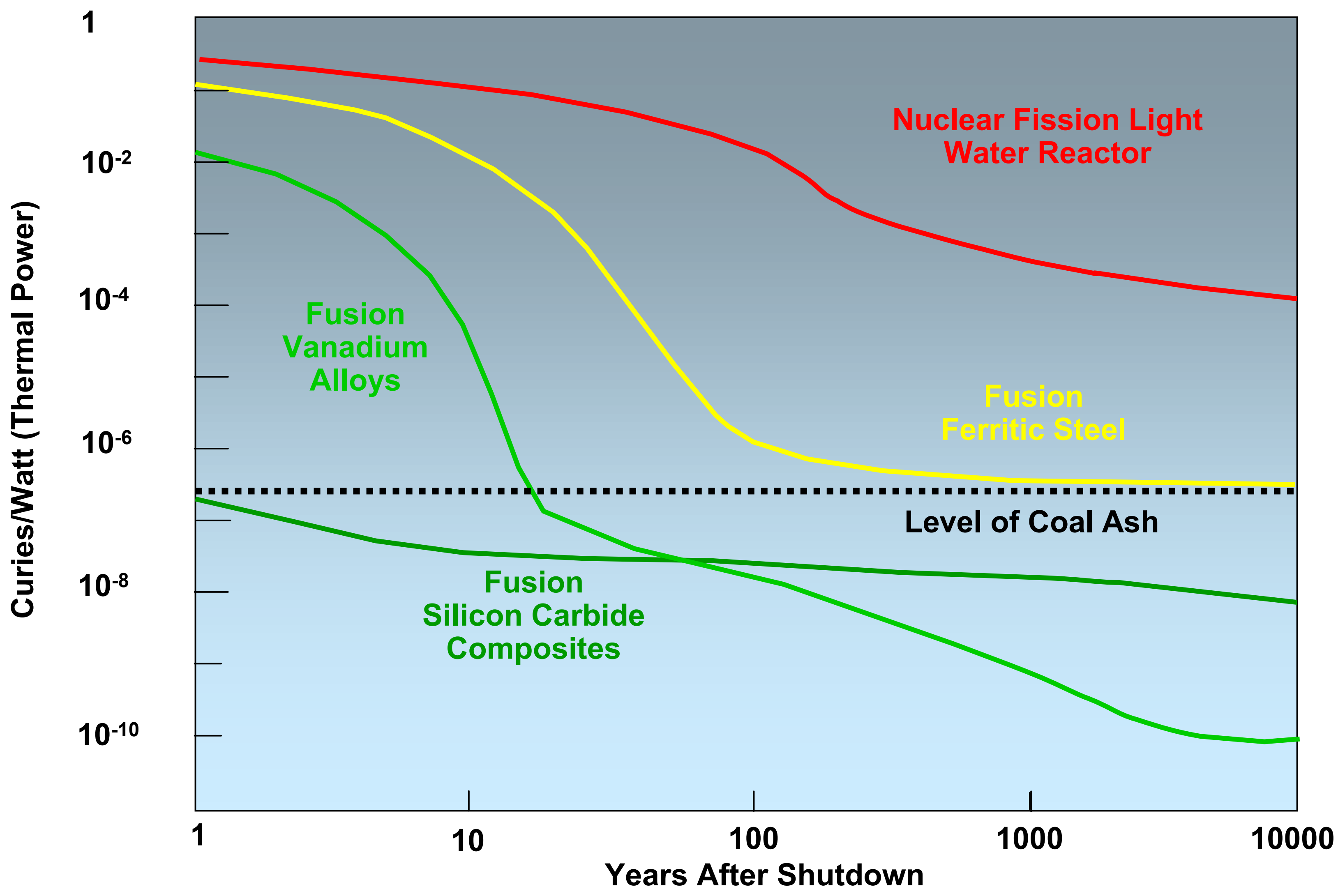
Schematic of a fusion power plant



Advantages of fusion energy

- High energy density fuel
  - 1g D-T → 26000kW-hr (1g coal → 0.003kW-hr)
- Abundant fuel, available everywhere
  - D is 1/6500 of H (OK for 10^{10} years)
  - Li is 17ppm of crustal rock (OK for 10^3 years)
- Environmental
  - no CO_2 emission
  - no high-level radioactive wastes
- No risk of nuclear accidents (<5min of fuel in reactor)
- No generation of weapons material
- Geographically concentrated, little use of land
- Not subject to local or seasonal variations

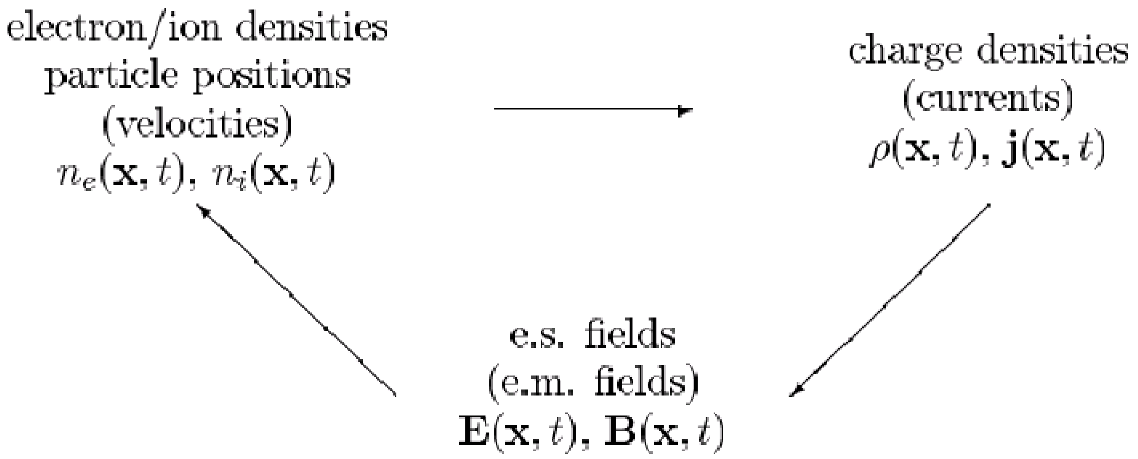
Comparison of activation in fusion and fission reactors



T~10keV: matter is under the form of plasma

Definition of a plasma

- Ensemble of changed particles, globally neutral



electron/ion densities
particle positions
(velocities)
$n_e(\mathbf{x},t)$, $n_i(\mathbf{x},t)$

charge densities
(currents)
$\rho(\mathbf{x},t)$, $\mathbf{j}(\mathbf{x},t)$

e.s. fields
(e.m. fields)
$\mathbf{E}(\mathbf{x},t)$, $\mathbf{B}(\mathbf{x},t)$

- Exhibiting collective behaviour
  - Local response to violation of neutrality

Static: screening of charge

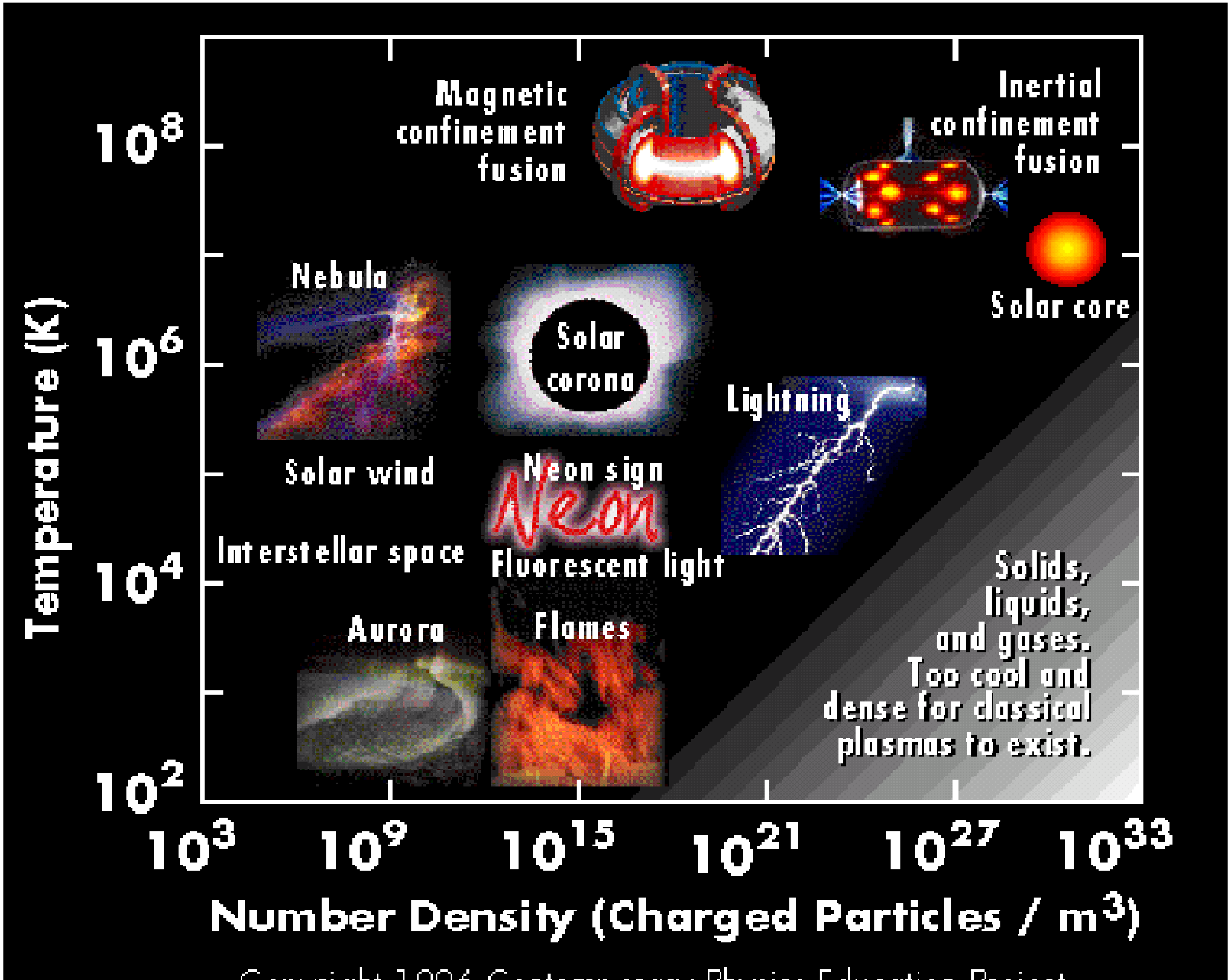
Debye length λ_D

$$\phi(r) = \frac{e}{4\pi\varepsilon_0}\frac{1}{r}\underbrace{\exp\left\{-\frac{r}{\lambda_D}\right\}}_{\text{term due to plasma collective interaction}} \qquad \lambda_D = \sqrt{\frac{T}{n_0 e^2/\varepsilon_0}}$$

Dynamical: plasma oscillations

$$\omega_p = \frac{1}{\tau} = \sqrt{\frac{e^2 n}{\varepsilon_0 m}} \quad \text{“plasma frequency”}$$

Examples of plasmas



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Images courtesy of DOE fusion labs, NASA, and Steve Albers.

Why *thermo*-nuclear fusion ?
A note on collisions in plasmas

Short range inelastic

- Charged particles – neutrals (ionisation)
- Nuclear (fusion reactions)

Long range ~ elastic

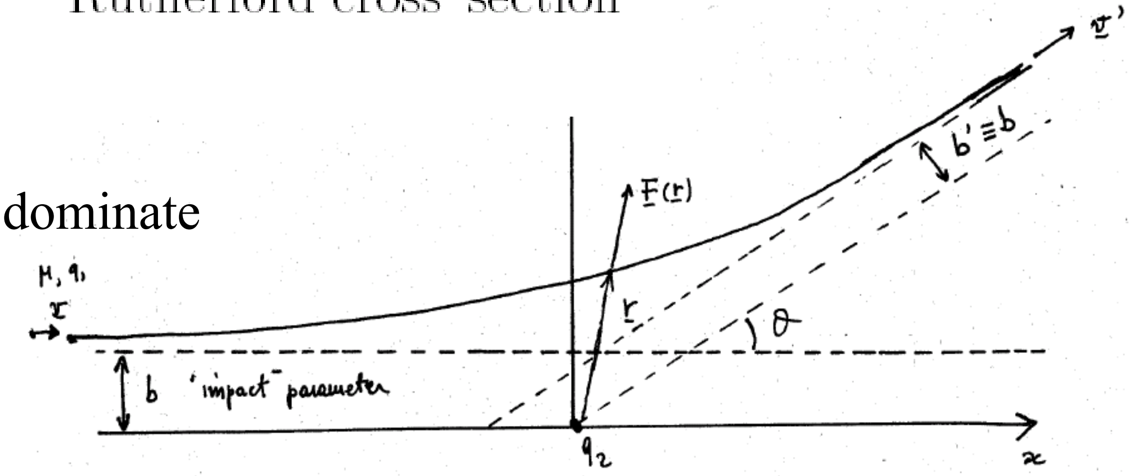
- Charged particles – charged particles (Coulomb)
  - Approximate many interactions within the Debye sphere with binary interaction, consider all possible collisions and average

$$\frac{d\sigma}{d\Omega} = \frac{b_{90}^2}{4\sin^4\frac{\theta}{2}} \propto \frac{1}{v^4\ \sin^4\frac{\theta}{2}}$$

"Rutherford cross–section"

For small θ: $d\sigma/d\Omega \propto \theta^{-4}$:

→Small angle collisions dominate



b_{90}: impact parameter for deflection of 90^0

Coulomb collisions: cumulative effects and effective collision frequencies

- Consider all scatterers, integrate over b and particle distribution
- Ex. effective collision frequency for energy exchange

$$\bar{\nu}_{E_k}^{e/i} = \frac{1}{E_k} \overbrace{\int f_e(\mathbf{v}_e) d^3v \underbrace{\int_{b_{min}}^{b_{max}} \frac{m_e v^2}{2} \frac{m_e}{m_i} \left(\frac{2b_{90}}{b}\right)^2 n\, v\, 2\pi b db}_{\int_{b_{min}}^{b_{max}} \Delta E_k\, n\, v\, d\sigma = \frac{dE_k}{dt}}}^{\left\langle \frac{dE_k}{dt} \right\rangle_f} = K \frac{n}{\boxed{T_e^{3/2}}}$$

Hotter → less collisional

$$K = \frac{2}{3}\sqrt{\frac{2}{\pi}} \frac{Z^2 e^4 m_e^{1/2}}{4\pi\varepsilon_0^2 m_i} \ln\Lambda\,, \qquad \Lambda \equiv \int_{b_{\min}}^{b_{\max}} \frac{db}{b}\,, \qquad \text{“Coulomb logarithm”}$$

- We are considering only small angles

$$\Longrightarrow \qquad b_{\min} \simeq max\{b_{90}, \lambda_{\text{DeBroglie}}\} \tag{7}$$

- Due to the Debye screening effect, outside the Debye sphere the potential is screened, so the Coulomb collisions are no more effective

$$\Longrightarrow \qquad b_{\max} \simeq \lambda_D. \tag{8}$$

Coulomb collisions: plasma resistivity

$$\eta = \frac{\sqrt{2}}{\pi^{3/2}} \frac{m_e^{1/2} Z e^2 \ln \Lambda}{12 \varepsilon_0^2 T_e^{3/2}} \propto T_e^{-3/2}$$

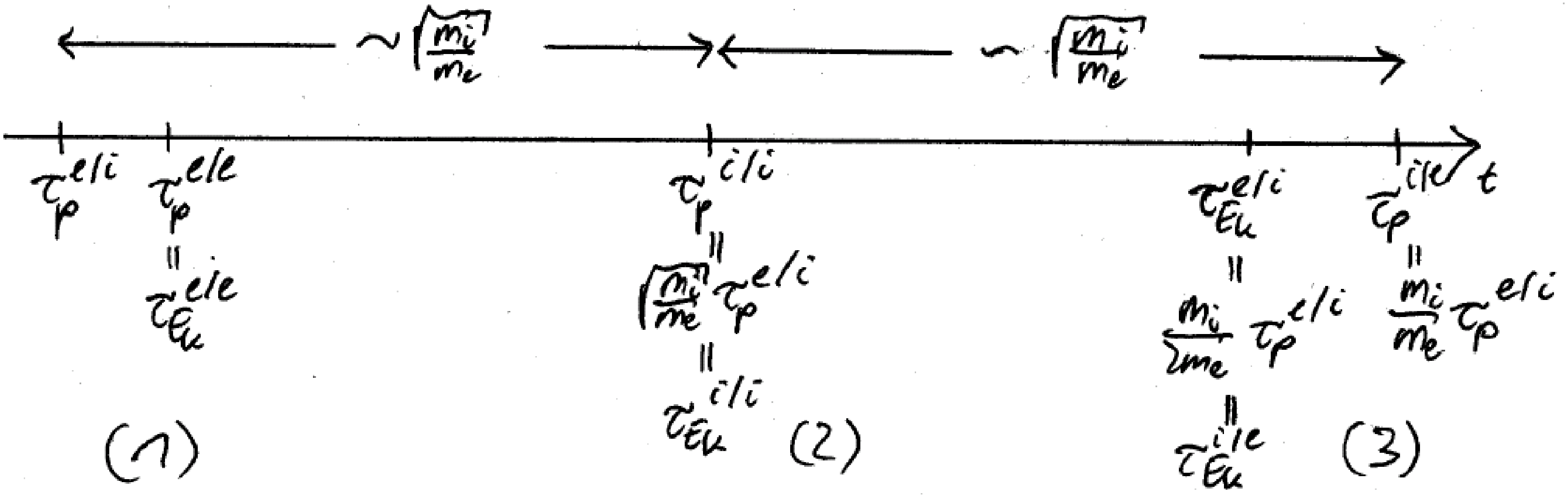
Resistivity - quantitative estimates

1. Plasma at 100 eV: $\eta \sim 6 \cdot 10^{-7}$ Ωm [$\sim \eta$ of stainless steel]
2. Plasma at 1 keV: $\eta \sim 2 \cdot 10^{-8}$ Ωm [$\sim \eta$ of copper]
3. For $T \gg 1$ keV plasma becomes almost superconducting

Observations The decrease of resistivity with temperature has two important consequences:

1. Magnetic flux is ‘frozen’ within plasma (e.g. solar wind carrying B–field with it)
2. Heating by current (‘ohmic heating’) becomes less and less effective at high T_e.

Coulomb collisions: characteristic time scales



- Ex. H plasma, $T_e = T_i = 10\text{keV}$; $n = 10^{20}\ \text{m}^{-3}$

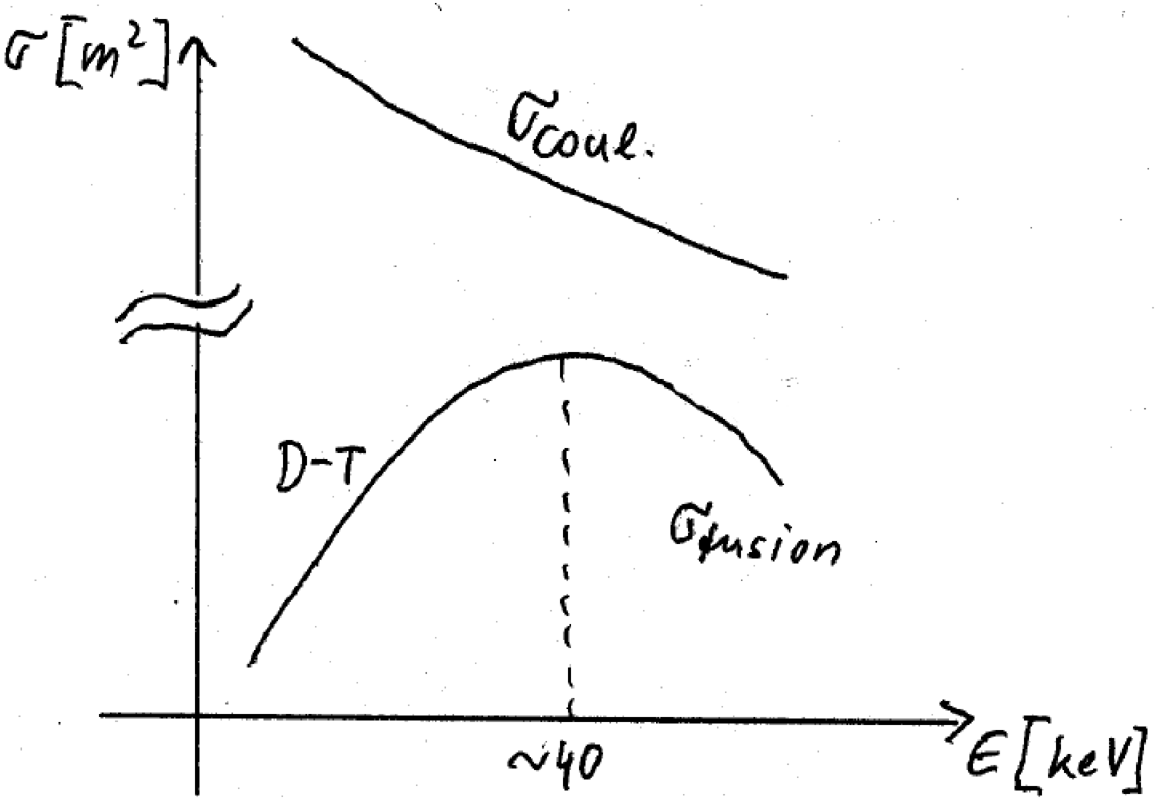
For momentum exchange and equilibrium within one species

$\tau_{p,Ek}^{e/e} \sim 0.2\text{ms}$; $\tau_{p,Ek}^{i/I} \sim 10\text{ms}$

For thermal equilibrium between the two species

$\tau_{Ek}^{e/i} \sim 0.5\text{s}$

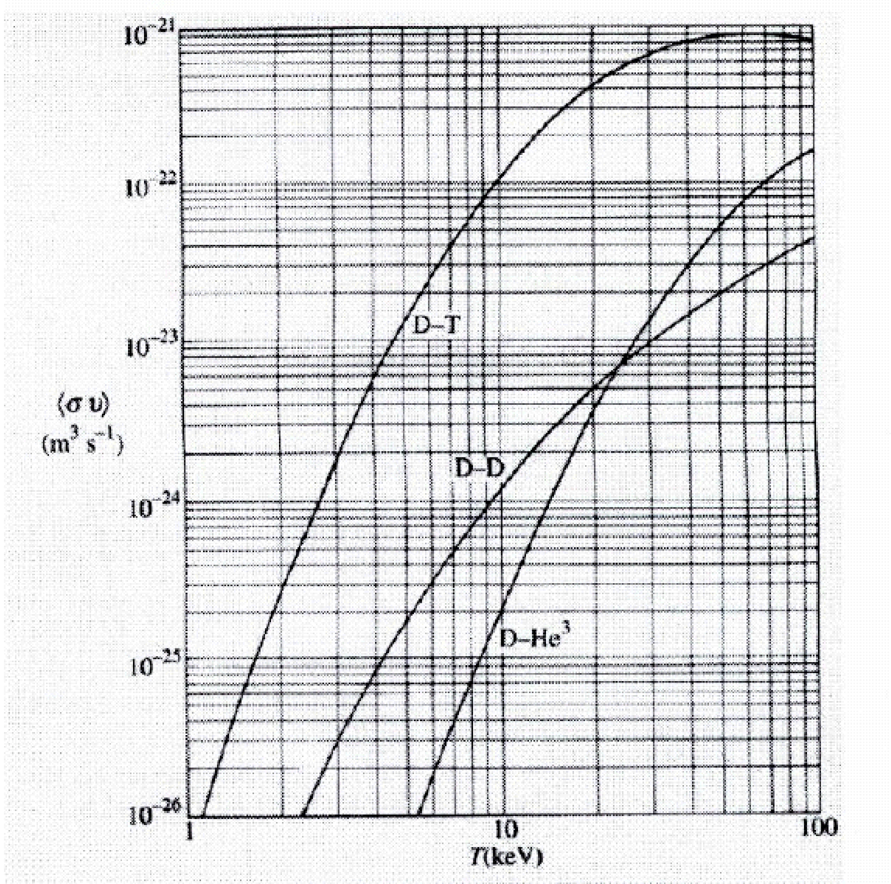
Coulomb collision σ is much larger than fusion σ for all energies



Fusion reactors must deal with 'thermal' plasmas

The Lawson criterion: energy production

- Fusion power density ≡ P_f $= n_D n_T <\sigma v> E_f$; E_f =17.6MeV
  $= \frac{1}{4} n^2 <\sigma v> E_f$ ($n_D = n_T = n/2$)
- Of this, 20% is in the α's: $P_\alpha = P_f/5$



- $<\sigma v>$ is the rate at which fusion reactions take place ('thermo-nuclear' fusion: we can average over Maxwellian distributions of D and T)
  - Ex.: $n = 5 \times 10^{20}$ m^{-3}, max($<\sigma v>$)
  - To have P_f ~1 GW we need a volume V~6 m^3
  - If only it was so easy….

The Lawson criterion: losses

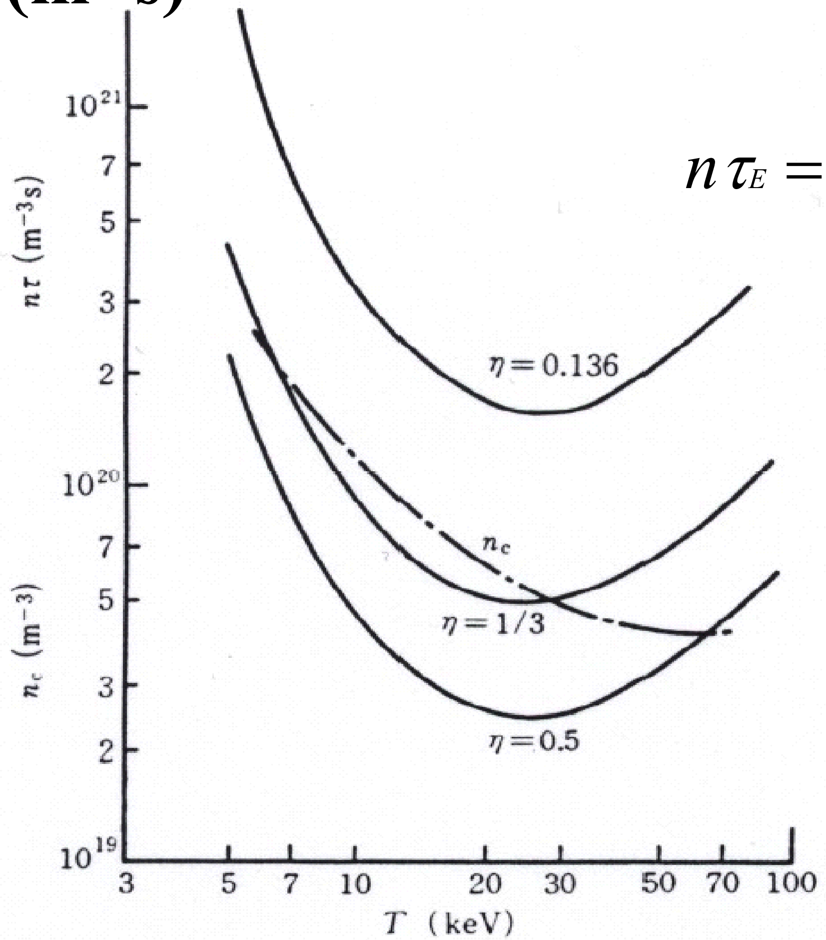
- Losses
  - Thermal energy density
    - $W \equiv 3nT$ is lost over characteristic time τ_E: $P_{loss} = W/\tau_E$
  - Bremstrahlung radiation
    - $P_b = A\, Z^2 n^2 T^{1/2}$ (X-rays)
  - Cyclotron emission
    - $P_{cycl} = C\, nT\, B^2$ (micro-waves)
    - but ~only for electrons, and mostly reabsorbed by plasma either directly or after reflection from metal walls → negligible
- Assumptions
  - Plasma is pure 50:50 D-T
  - Efficiency of conversion of thermal energy into electricity $= \eta_1$
  - Efficiency of conversion of electricity into plasma heating $= \eta_2$
  - Total efficiency $\eta = \eta_1 \eta_2$
  - The power density re-injected in plasma is $\eta(W/\tau_E + P_b + P_f)$

The Lawson criterion: breakeven

- **Breakeven: Power reinjected = Losses**

$$\eta(W/\tau_E + P_b + P_f) = W/\tau_E + P_b$$

nτ ($m^{-3}s$)



T (keV)

$$n\tau_E = \frac{3T}{\frac{\eta}{1-\eta}\frac{\langle \sigma v\rangle}{4}E_f - AT^{1/2}} = fct(T)$$

The Lawson criterion: ignition

- **If α's are confined, external heating is not needed (and bremstrahlung can be neglected) if $P_\alpha = W/\tau_E$**

Ignition condition

$$n\tau_E = \frac{3T}{\frac{\langle\sigma v\rangle}{4}E_\alpha} = fct(T)$$

  - **Ignition condition←→ *efficiency* $\eta = 1/(1+E_\alpha/E_f^{\,total}) = 0.136$**

  - **Fusion energy gain: $Q \equiv P_{fusion}/P_{heat} = 5\,P_\alpha/P_{heat}$**
  - **α heating fraction: $f_\alpha \equiv P_\alpha/(P_\alpha+P_{heat}) = Q/(Q+5)$**

Q=1 **f_α=17% *breakeven***

Q=5 **f_α=50%**

Q=∞ **f_α=100% *ignition***

↓ ***burning plasma***

- ***Need*** $n\tau_E \sim 10^{21}\ m^{-3}s$ ***at*** $T \sim 10keV$

confinement ***heating***

Plasma confinement

- ***Magnetic***

  $n \sim 10^{20}\ m^{-3}$

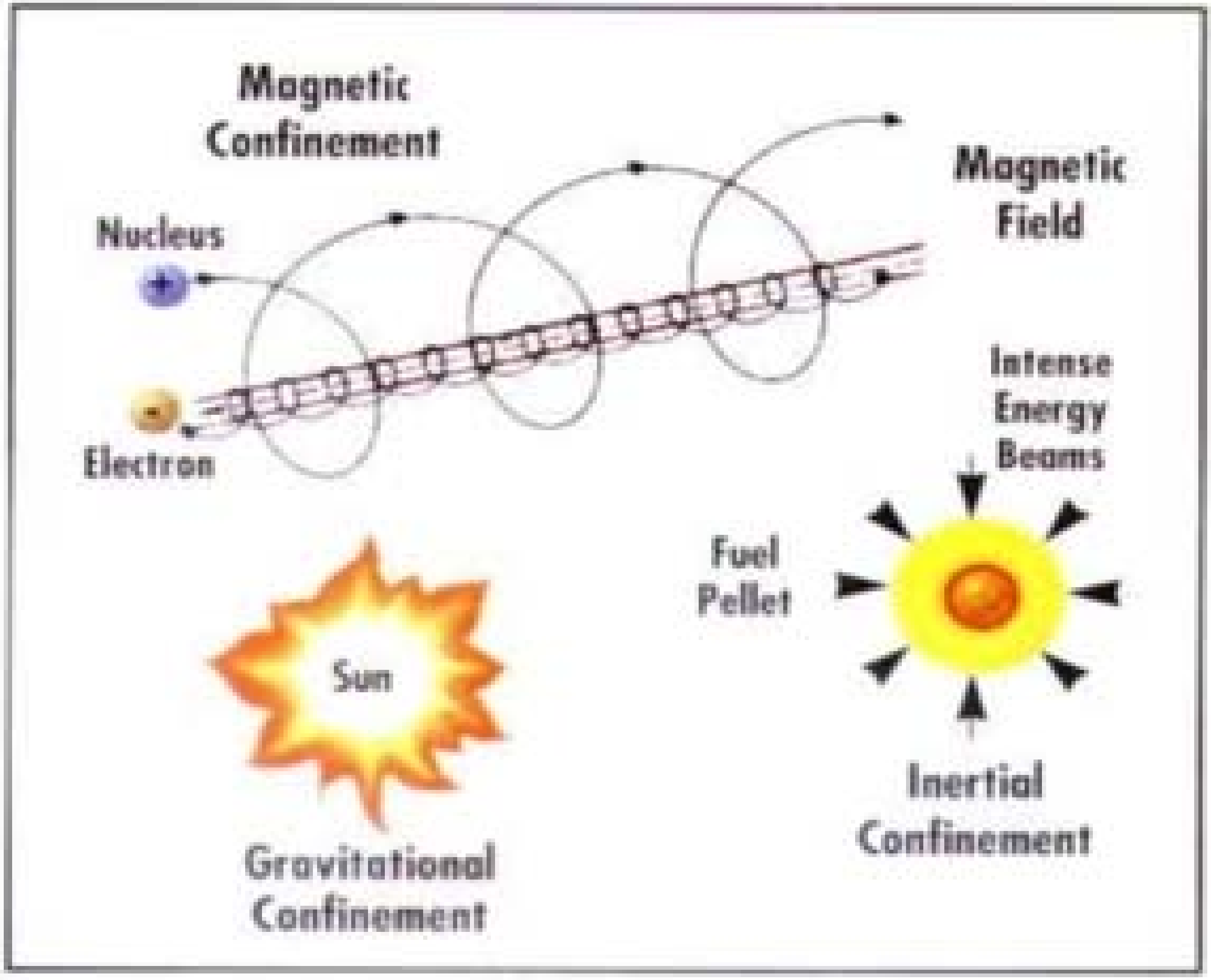
  $\tau_E \sim 10\ s$

- ***Inertial***

  $n \sim 10^{31}\ m^{-3}$

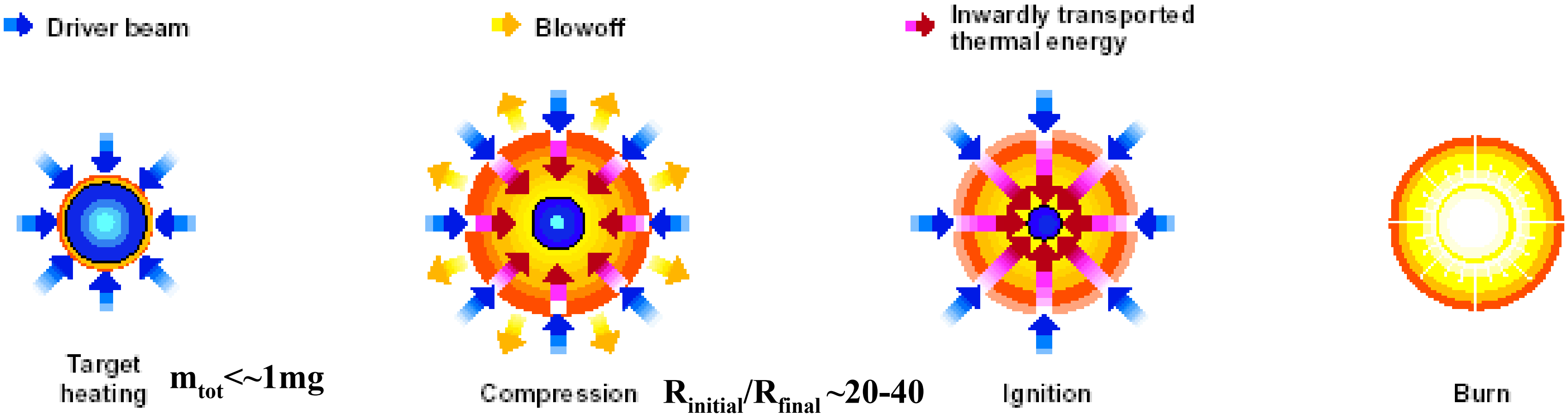
  $\tau_E \sim 10^{-10}\ s$

- ***Need to confine and heat the plasma***



Inertial Confinement Fusion

– A capsule with D-T is irradiated by lasers, X-rays, or particle beam



$m_{tot} <\sim 1\text{mg}$ $R_{initial}/R_{final} \sim 20\text{-}40$

– Compression: need ~ 10^{12} bar to reach 10^{31}m^{-3}

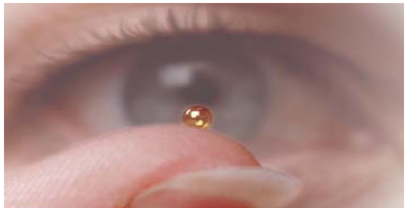
  - Laser with 10^{16} W/cm² $\rightarrow p_{light} \sim 10^6$ bar, largely insufficient
  - Shock waves at the pellet surface, arriving at the center at the same time
  - Once fusion starts, α heating sustains the reactions

– Heating to ignition must occur before ions fly away

  - Energy flux F: $\tau_{heat} = U_{th}/(4\pi R^2 F)$; $U_{th} = 3nT(4/3\pi R^3)$

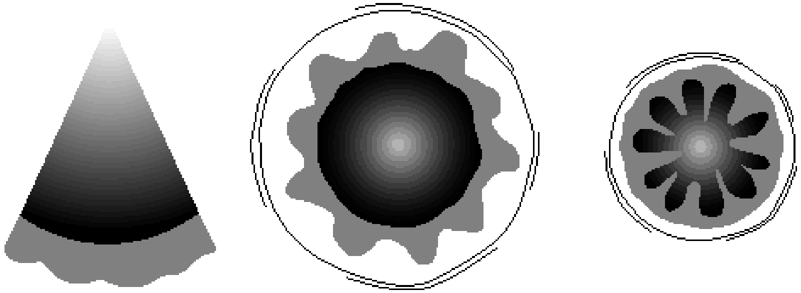
    $\tau_{heat} <$ inertial time $= R/v_{sound}$ (~100ps)

  $\rightarrow F > nT^{3/2}/m_i^{1/2} \sim 5\times 10^{15}$ W/cm²



ICF: general issues

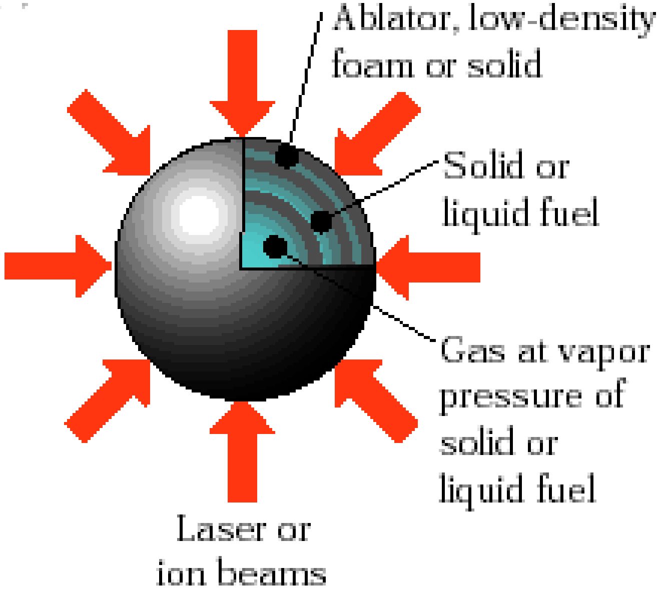
- Uniformity, stability of compression
  - Rayleigh-Taylor hydro-dynamic instability
    - Low density vaporised shell pushes high density D-T ice layer
    - Magnifies surface irregularities and may prevent ignition

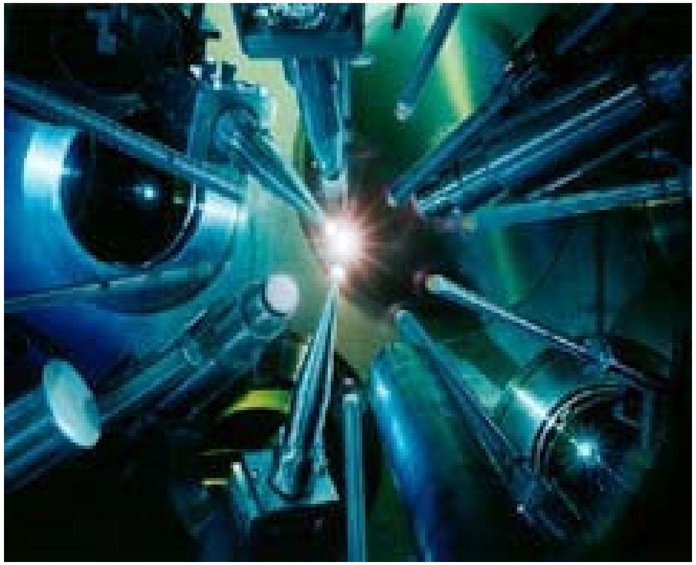


  - Capsule design
- Efficiency of drivers
- Steady-state: extension of techniques from single pulse to many repetitive pulses for energy production
- Materials for first wall
  - Long lifetime, low induced radio-activity, …
- Optimisation to reduce cost and increase efficiency

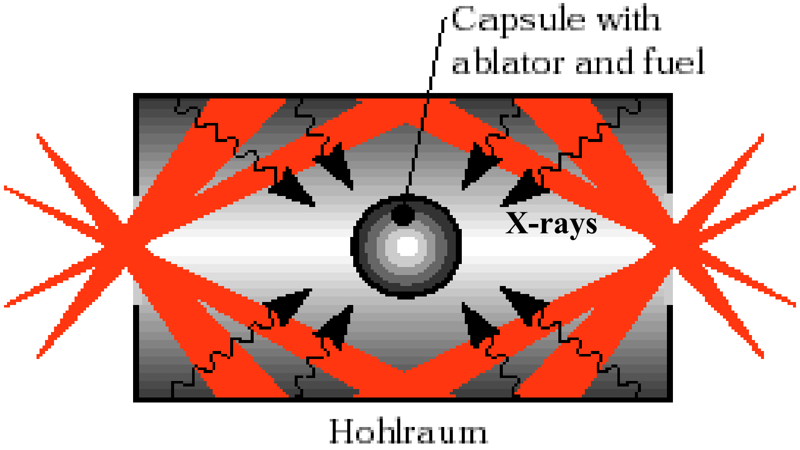
ICF: direct and indirect drive

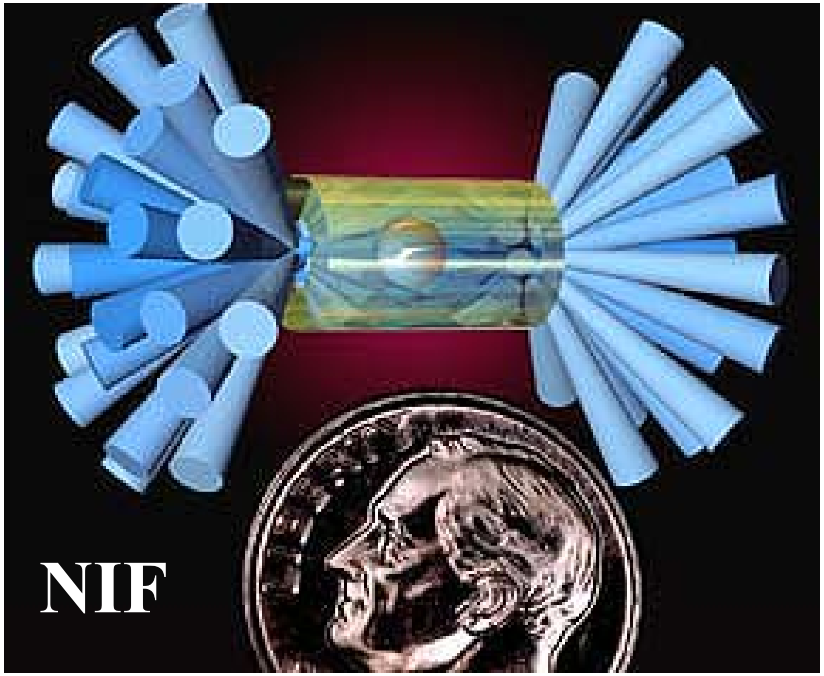
Direct drive





Indirect drive



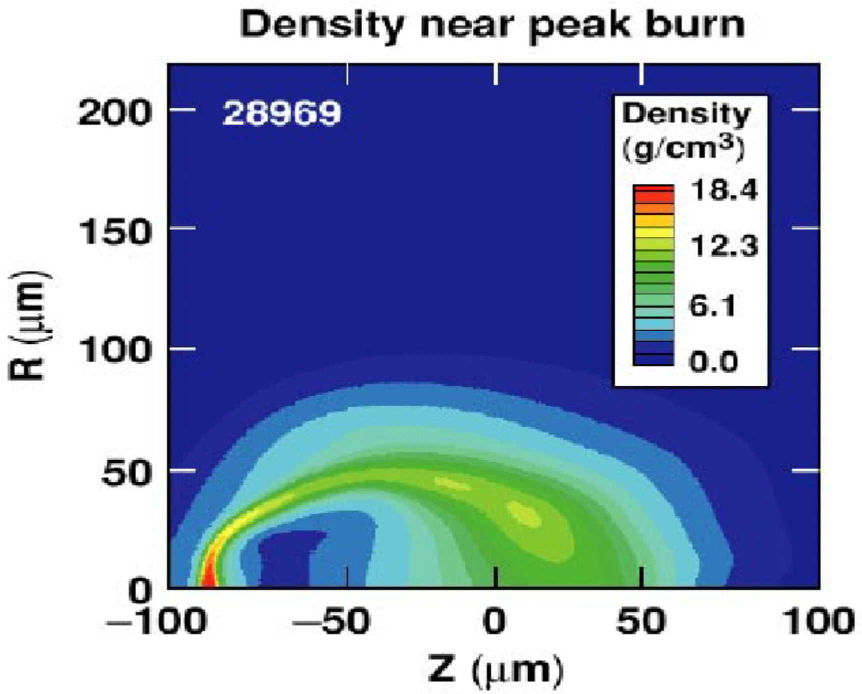


ICF – direct drive: ex. of results

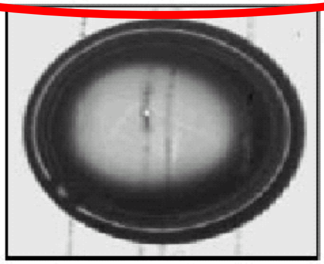
Initial 2D hydrodynamic simulations show good agreement with experimental α=4 cryogenic target results

UR LLE

DRACO code simulated density contours



α = 4 pulse, 17 kJ
100-μm thick ice layer
8-μm rms ice roughness



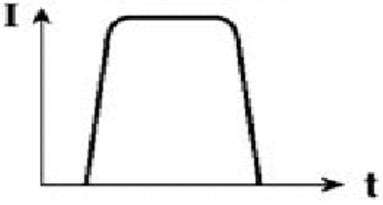
	Expt	1-D	2-D
Y_{1n}	5.95×10^9	5.60×10^{10}	5.32×10^9
Y_2	6.75×10^7	6.94×10^8	6.31×10^7
$<\rho R>$	67	80.0	58
T_{ion}	2.5	1.7	2.0

T.C.Sangster et al. Phys. Plasmas 10, 1937 (2003

$\alpha = P_{fuel}/P_{Fermi}$

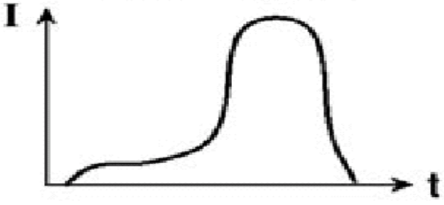
P_{Fermi}=Fermi degenerate pressure

High α-pulse



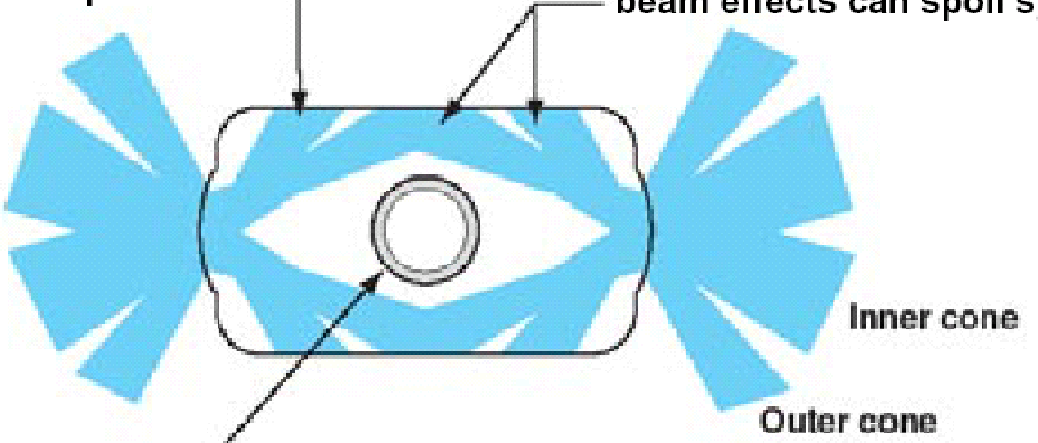
Good stability

Low α-pulse



High gain

ICF – indirect drive: issues



Hohlraum Energetics

- Backscatter reduces laser absorption and energy coupled into the capsule

Indirect Drive Symmetry

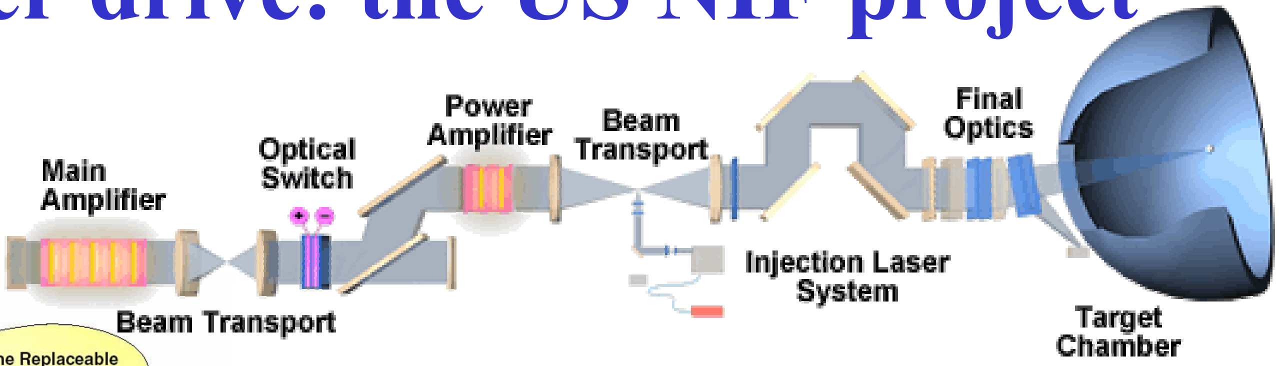
- Unequal absorption between cones can spoil beam balance
- Beam bending, beam spray and cross beam effects can spoil symmetry

Implosion/compression to high density

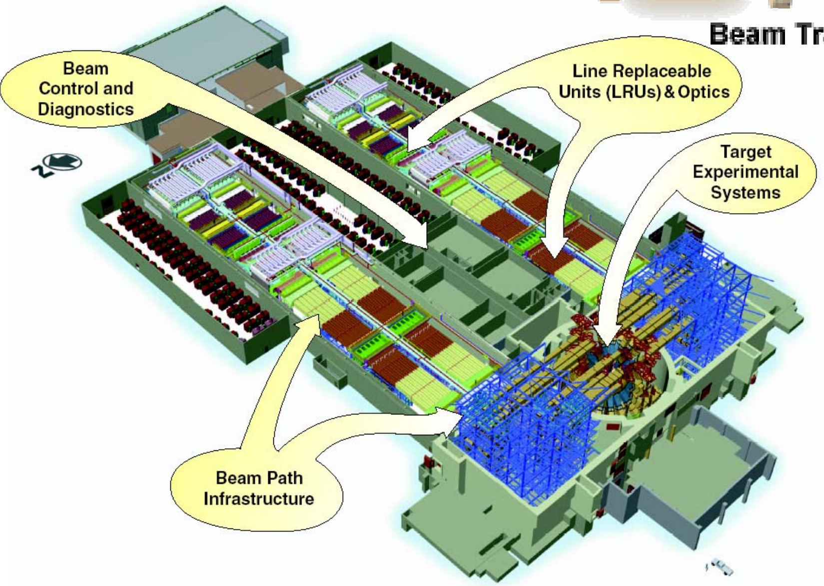
- Time dependent scatter can spoil pulse shape
- Hot electrons from plasma waves can preheat the fuel making it less compressible

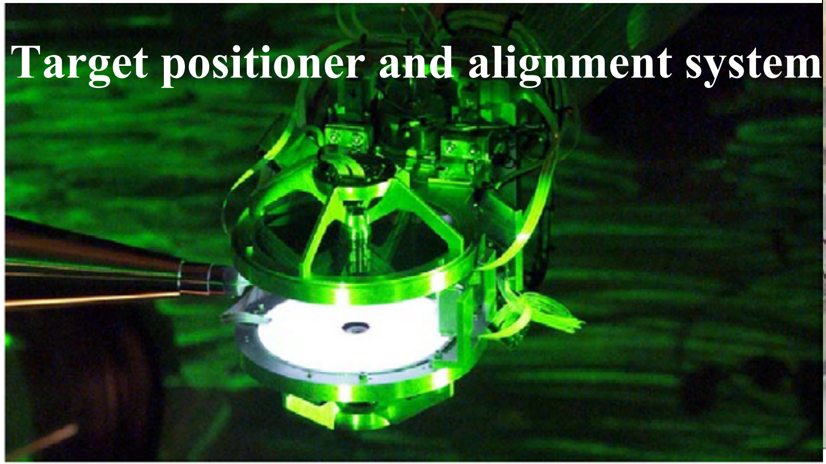
– Ex. of avenue for optimisation: higher holraum T → higher p, implosion velocity, compression → ignition with less energy

ICF – laser drive: the US NIF project



~2009: 192 beams, ~1.8MJ, 500TW UV light (0.35μm); fusion yield~20MJ





Target positioner and alignment system

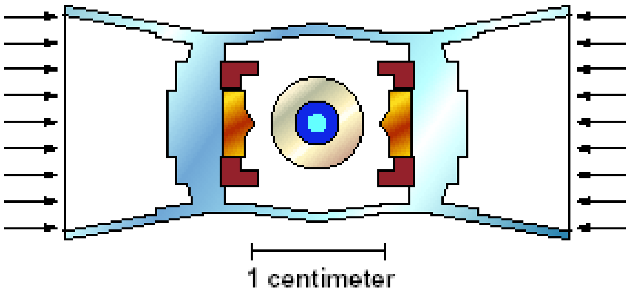
Target chamber

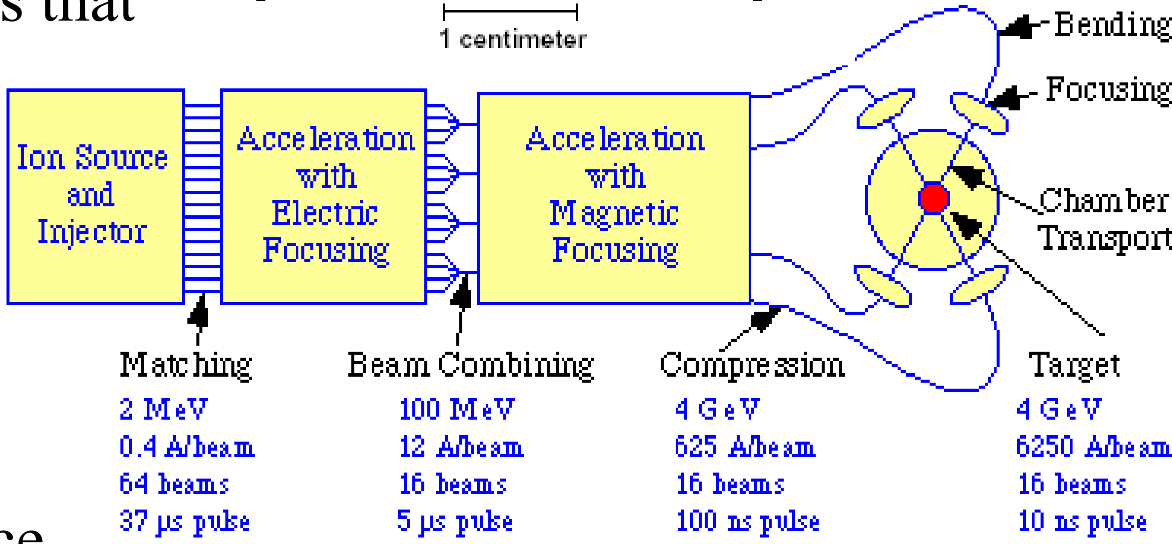
ICF – laser drive developments

- Today's laser drivers are limited for power plant use by
  - Efficiency (should be >5%)
  - Repetition rate (should be >0.1Hz)
  - Damage to injection windows/mirrors by heat, n, debris
- New laser developments
  - Diode-Pumped Solid-State Laser Driver
    - Diodes instead of flashlamps to pump a solid-state laser could permit rapidly repeated firings, efficiency needed for power generation
      - Ex. Mercury laser at LLNL should reach: 100J, 10Hz, 10% efficiency, 3ns
  - Krypton-Flouride Gas Laser Driver
    - With the KrF laser (0.248μm), the laser medium is a gas that can be circulated for heat removal to achieve high repetition rate
- Other driver methods
  - **Ion beams (indirect drive)**
  - **High rep rate z-pinches**

ICF – ion beam indirect drive

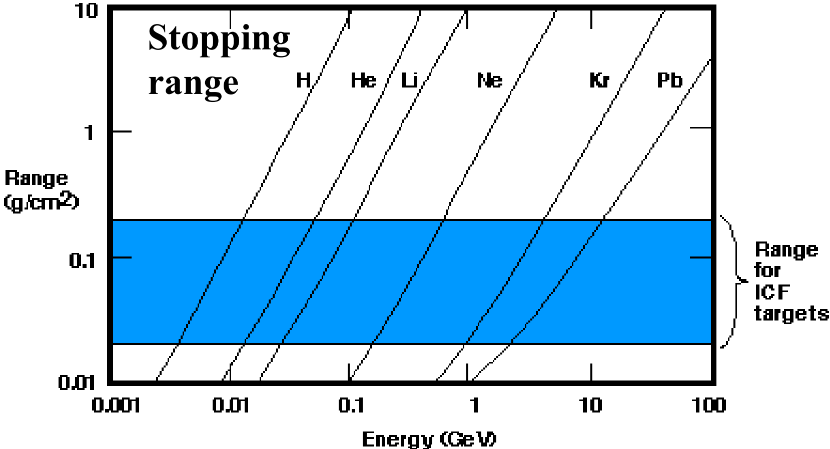
- Heavy ion beams
  - Ions hit target, energy gets converted into X-rays that compress pellet
  - Ex. Cs ions, 400 TW





Matching	Beam Combining	Compression	Target
2 MeV	100 MeV	4 GeV	4 GeV
0.4 A/beam	12 A/beam	625 A/beam	6250 A/beam
64 beams	16 beams	16 beams	16 beams
37 μs pulse	5 μs pulse	100 ns pulse	10 ns pulse

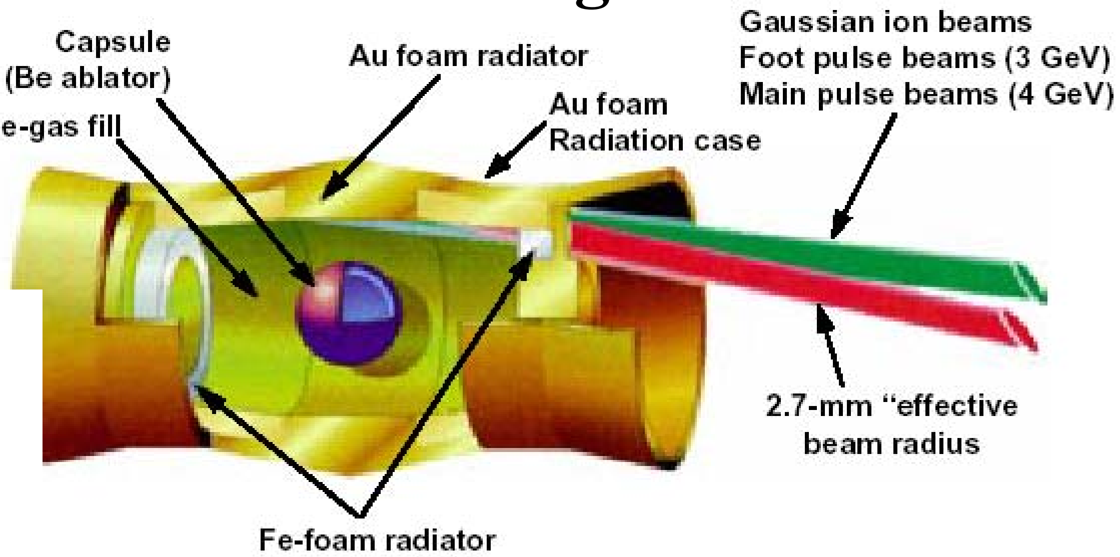
- Challenges
  - Beam transport, space-charge, emittance
  - Pulse compression
  - Focus and deposition depth (light vs. heavy ions) ⟶
  - Cost, but one accelerator could drive many target chambers



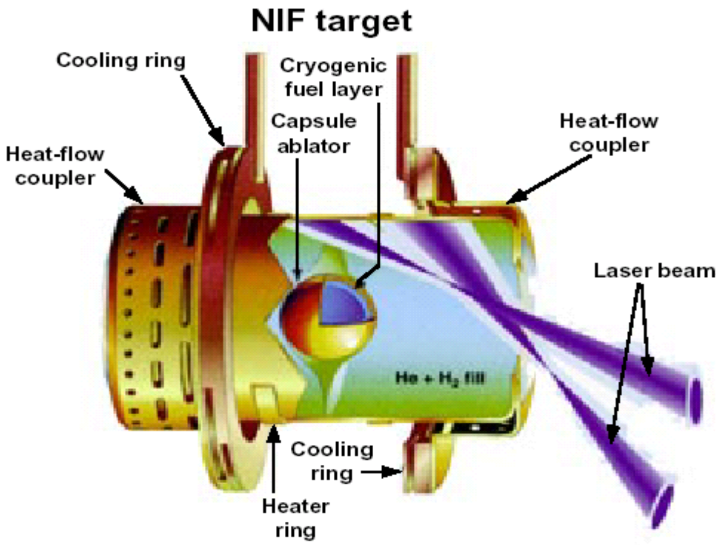
ICF – heavy ion beam target

- Similar issues to laser drive
  - Stability, ignition and burn propagation, symmetry control

Ion beam target



Laser target



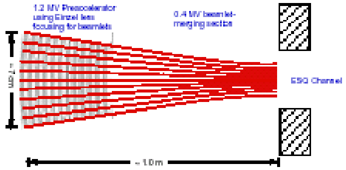
Yield = 400 MJ
Driver (using NIF-like hohlraum to capsule radius ratio)
6 MJ of 4 GeV Pb ions ▯ gain 67
7.5 MJ of 8 GeV Pb ions ▯ gain 53

ICF – heavy ion driver: future developments

The heavy ion fusion program plans consists of distinct experiments on ion sources, beam transport, and focusing to be followed by an integrated beam experiment

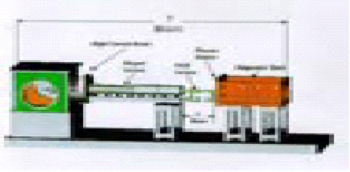
NOW (next three years)

Brighter sources/ injector

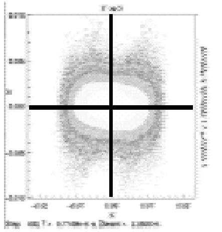


Maximum <J >, B_n Transport

Beam neutralization → min ε-limited focus r_f

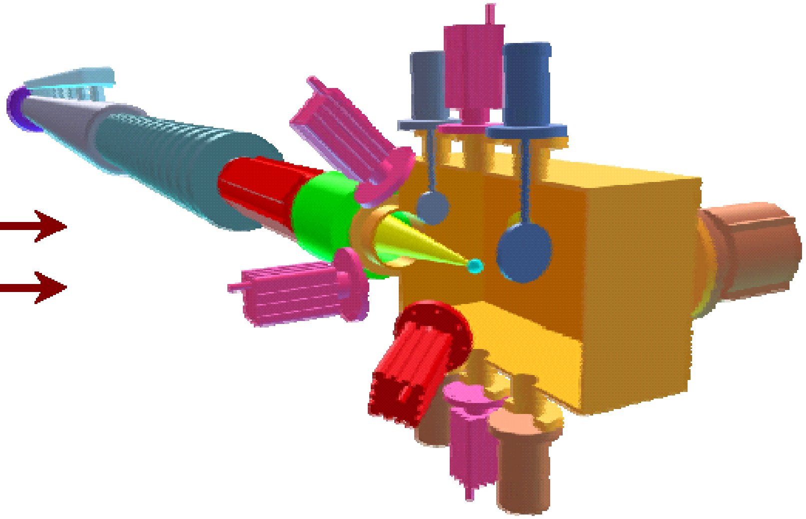


Theory/simulations



NEXT STEP

integrated beam experiments (IBX)

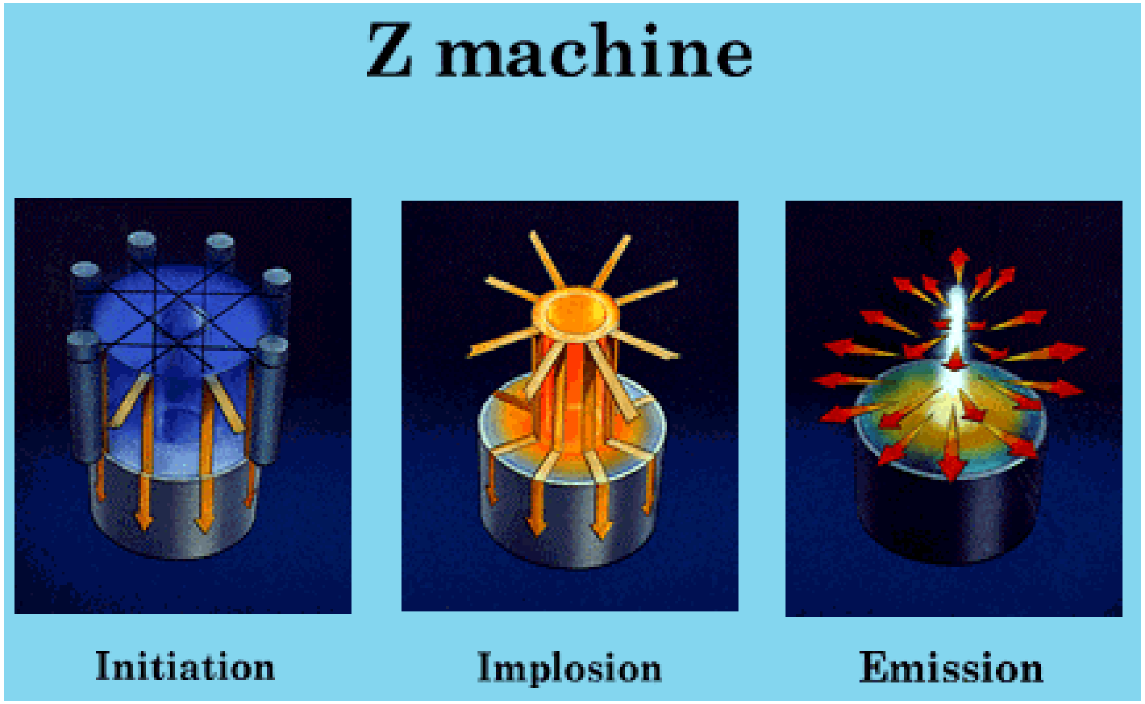


...to test source-to-target-integrated modeling

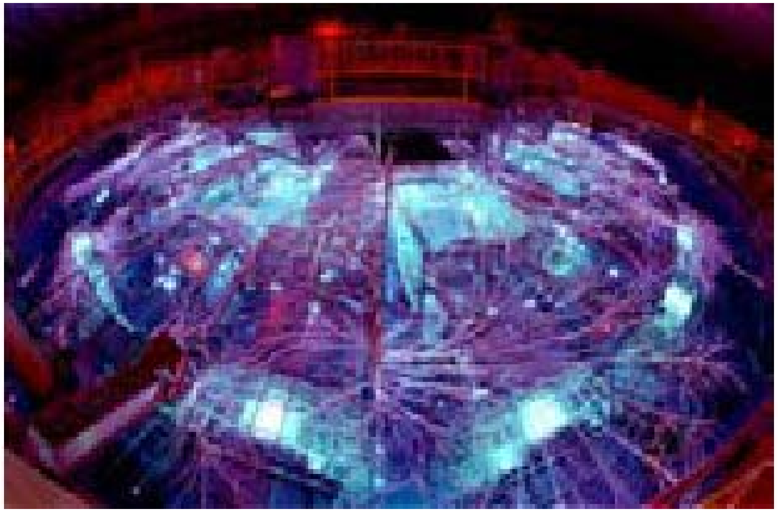
(Injection, acceleration, longitudinal compression and final focus)

ICF – drive by X-rays from z-pinch

- Ex. Sandia NL
  - 360 tungsten wires (~1/10 of human hair) collapse, evaporate, form a plasma in high current pulse
  - Plasma emits X-rays:
    T~150eV
    E~2.0MJ
    P~100TW
  - Next generation: ~16MJ ?

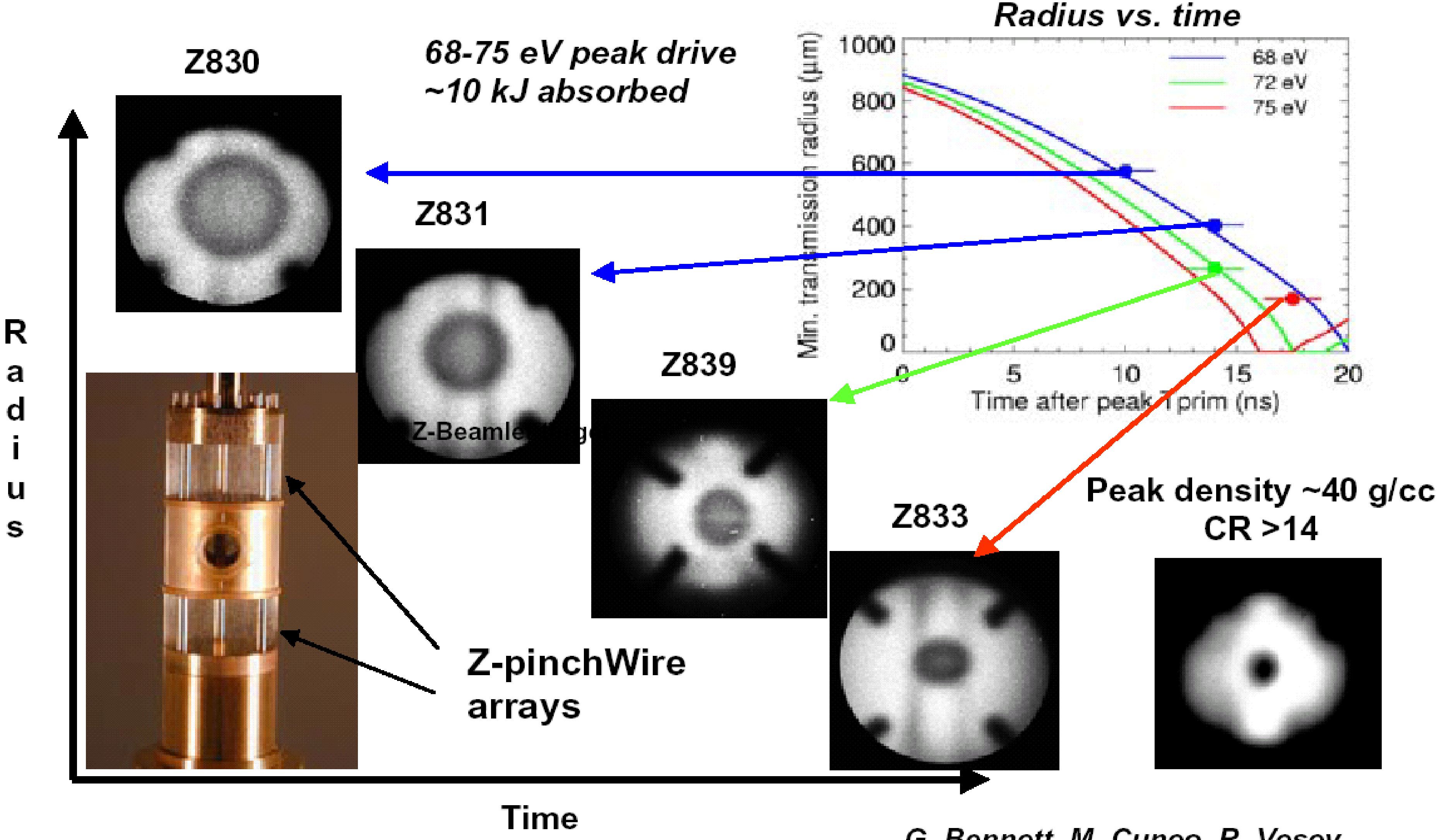


X-rays-
Z –machine
(Sandia)



ICF – drive by X-rays from z-pinch

Progress in the symmetry of implosion of targets driven by indirect drive from double z-pinch



68-75 eV peak drive
~10 kJ absorbed

Z830

Z831

Z839

Z833

Peak density ~40 g/cc
CR >14

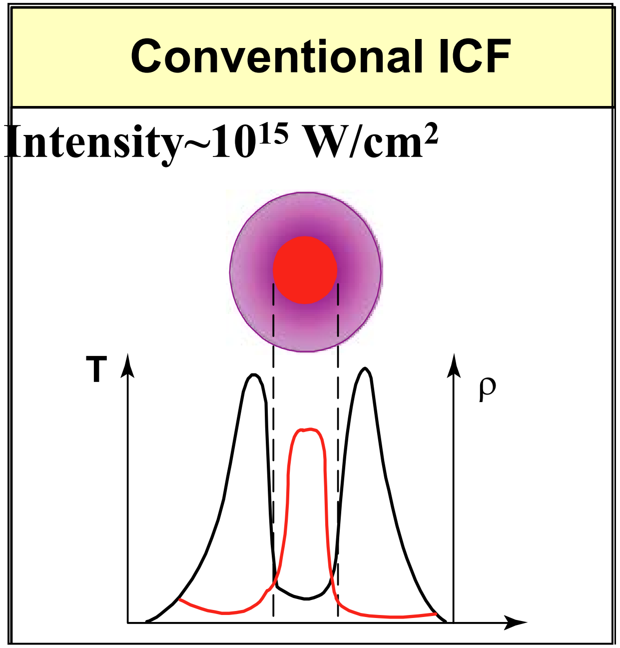
Z-pinchWire arrays

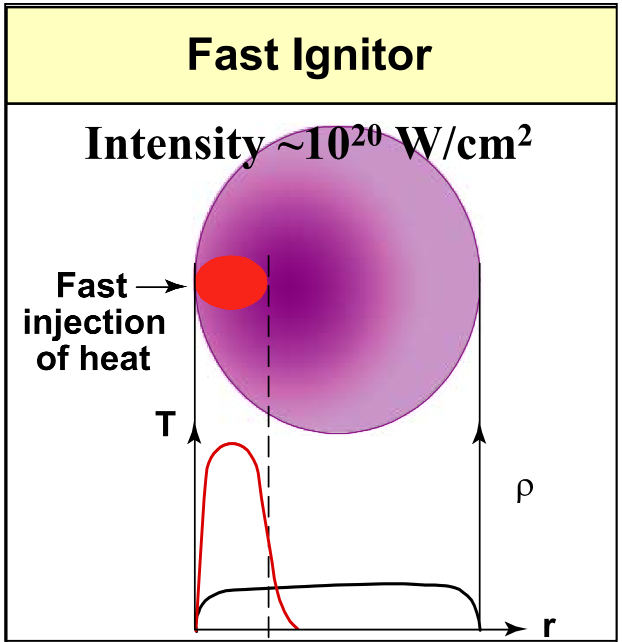
G. Bennett, M. Cuneo, R. Vesey

ICF: fast ignition

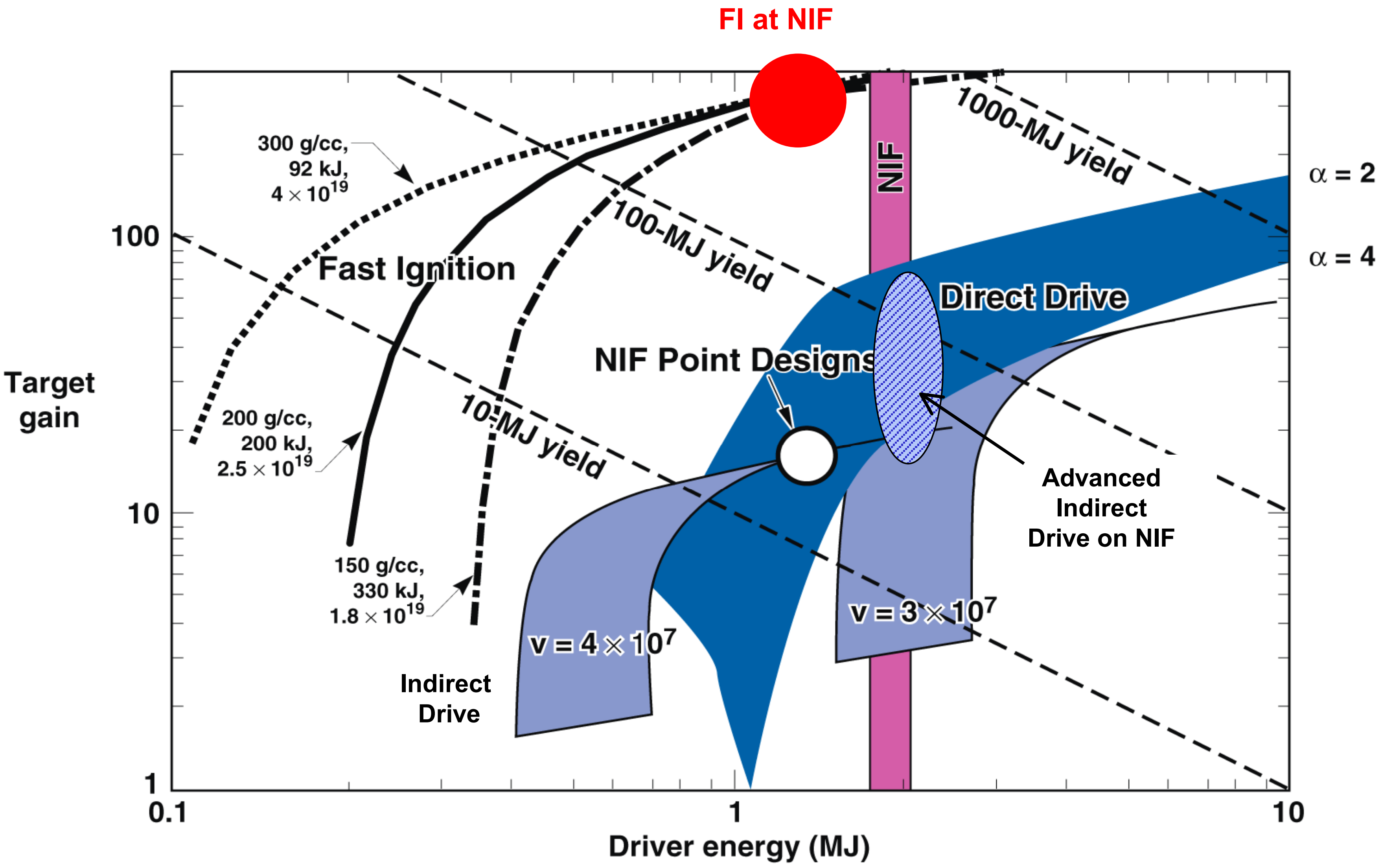
- Conventional ICF
  - D-T gas compressed by imploding solid D-T must form fusion ‘hot spot’, igniting and generating symmetrically propagating burn
  - Even if implosion is uniform, if hot spot is not symmetric, it squirts out, mixes with colder D-T and burn is prevented
- Fast ignition
  - Idea: decouple compression and ignition
  - No need for hot spot: at max compression, a very short ($<10^{-11}$s) power pulse is injected on the side

→ ***lower energy, inexpensive drivers could be used for simpler task of compressing fusion fuel if no need for a hot spot***

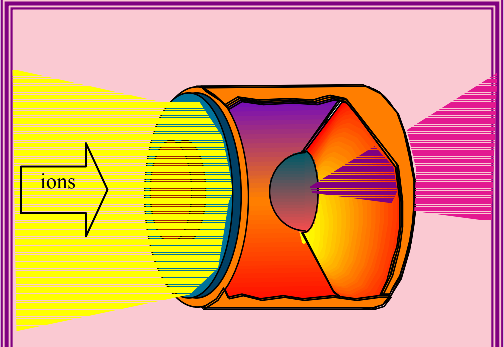




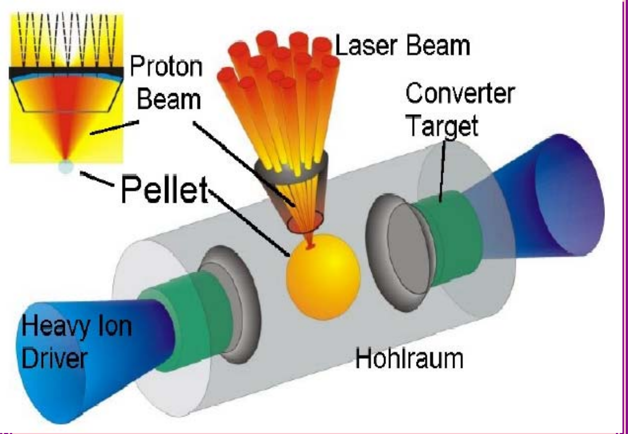
ICF: fast ignition may give higher gain



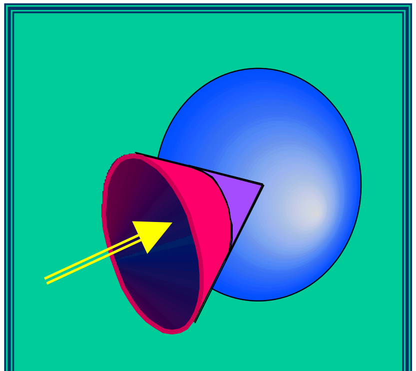
Fast ignition is compatible with all drivers



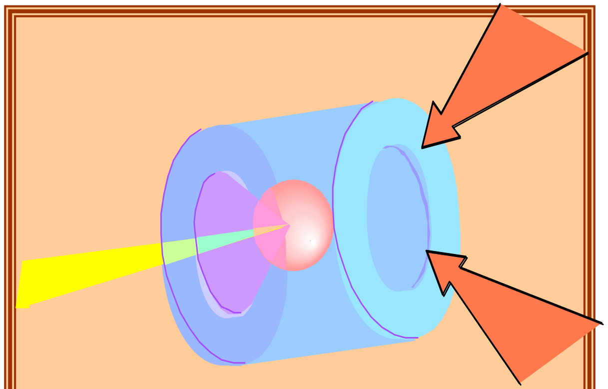
Heavy Ion Beam Drive



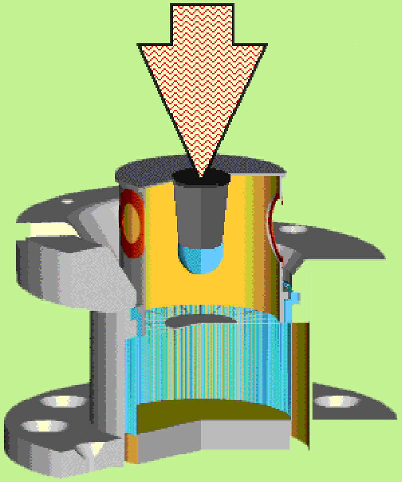
Heavy Ion Beam Drive



Direct Laser drive
with cone focus



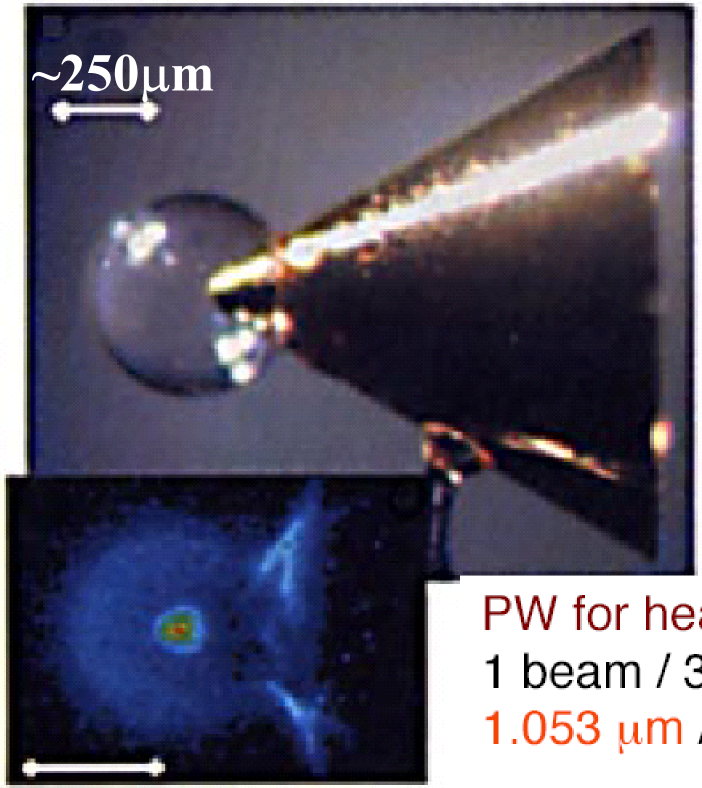
Indirect Laser drive



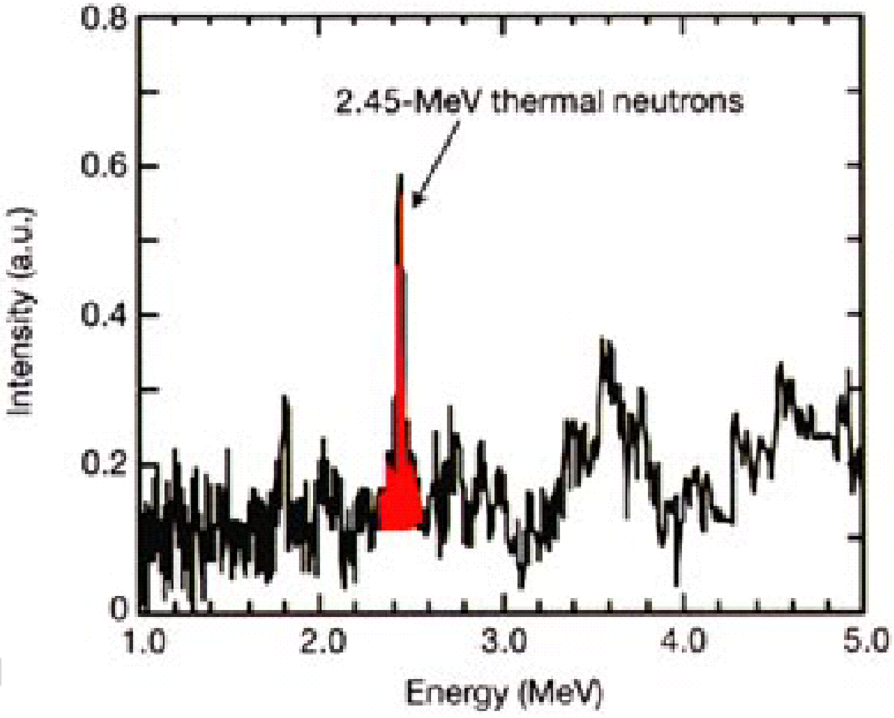
Z-pinch Drive

ICF – fast ignition: promising results?

Enhanced neutron output from fast heating of deuterated direct drive shell implosion on Gekko XIII laser (Japan,UK) R. Kodama, et al., Nature 412, 798 (2001)



PW for heating
1 beam / 300 J
1.053 µm / 0.5ps



1.2 KJ compression pulse + 60 J, 100 tw fast heating pulse

Green lasers, t = 1-2 nsec.
$\sim 10^{14}$ W/cm^2

1 µm laser, t=0.5ps
$\sim 10^{19}$ W/cm^2

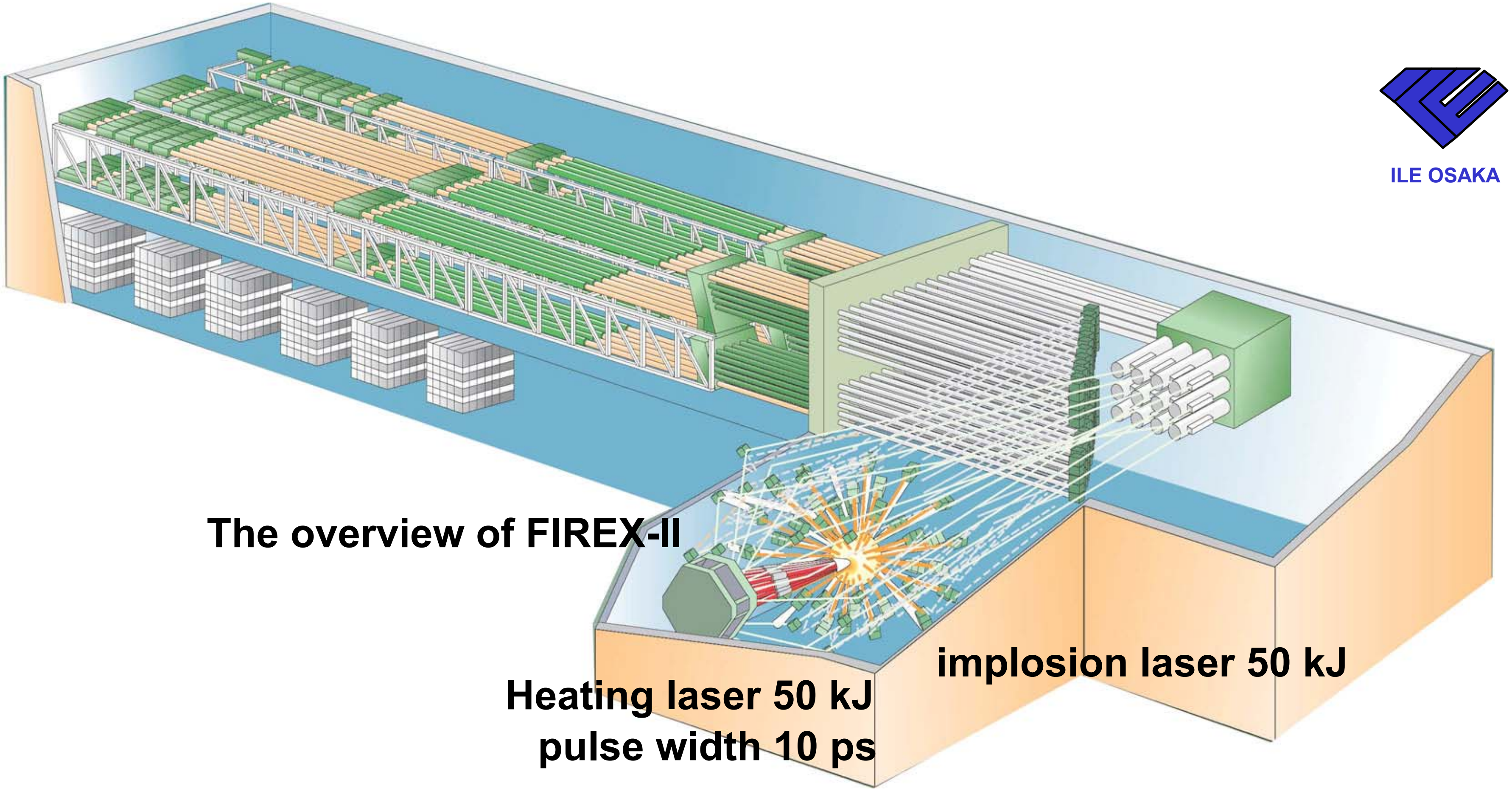
ICF – FI medium term development in Japan

FIREX (Fast Ignition Realization Experiment)

Purpose: Establishment of fast ignition physics and ignition demonstration

Starting Conditions: high density compression (already achieved)
heating by PW laser (1keV already achieved)

ILE OSAKA



The overview of FIREX-II

Heating laser 50 kJ
pulse width 10 ps

implosion laser 50 kJ

Foreseen ICF development steps (US view)

Phase I:
Basic fusion
science &
technology
1999- 2008

Scalable Technologies
- Krypton fluoride laser
- Diode pumped solid state laser
- Heavy Ion Accelerators
- Rep-rated Z pinch
- Chambers materials/design
- Target fabrication

Target design & Physics
- 2D/3D simulations
- 1-30 kJ laser-target expts
- MJ Z pinch expts

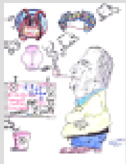
Phase II
Validate
science &
technology
2009 - 2020

Full Scale Components
- Power plant beamline (IRE)
- Target fab/injection facility
- Power Plant design

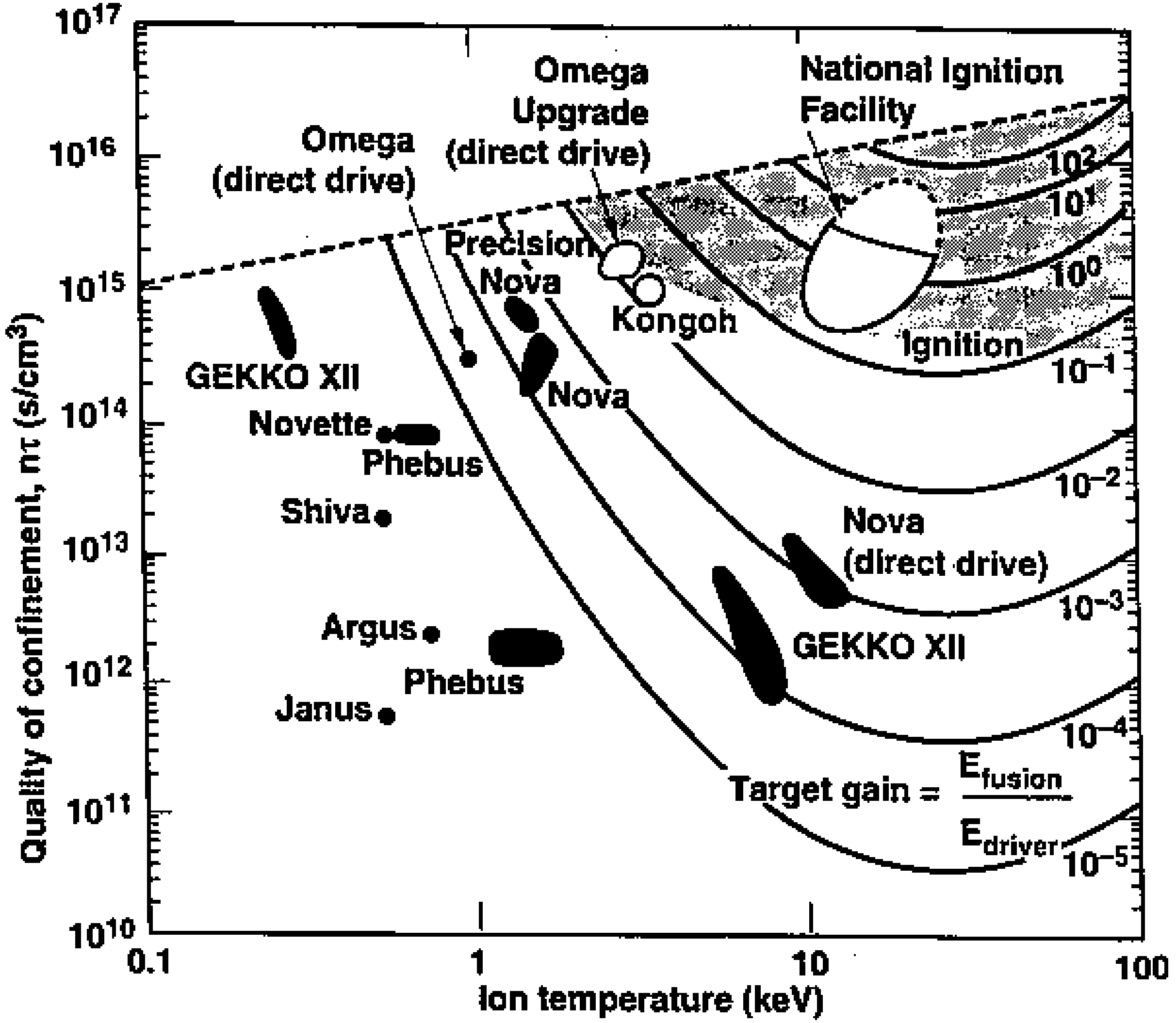
Ignition Physics Validation
- MJ target implosions
- Calibrated 3D simulations

Phase III
Engineering
Test Facility
operating ~ 2030

- *Full size driver*
- *Optimize targets for high yield*
- *Develop materials and components.*
- *~ 300-700 MW net electricity*

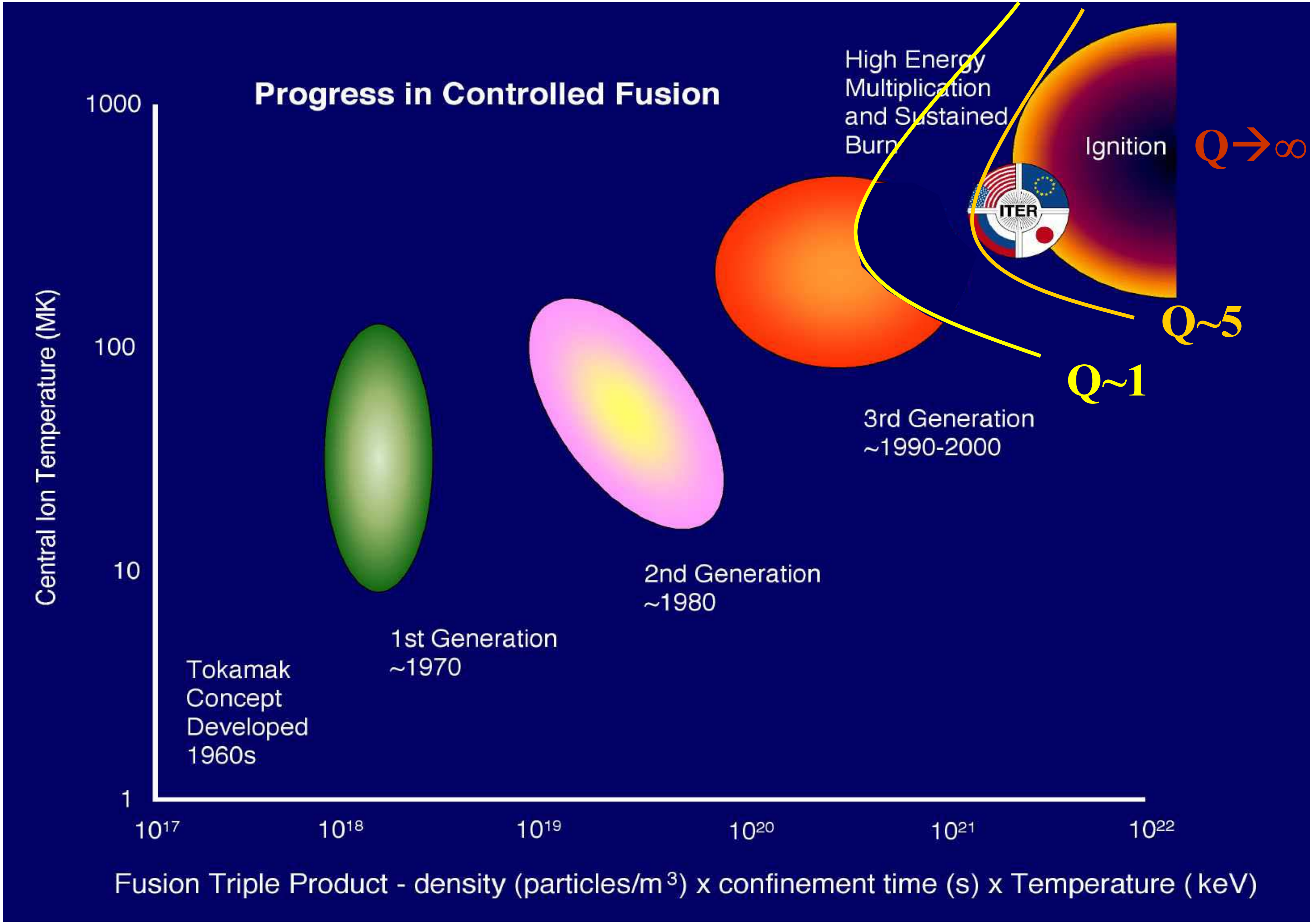


Summary of progress in inertial fusion

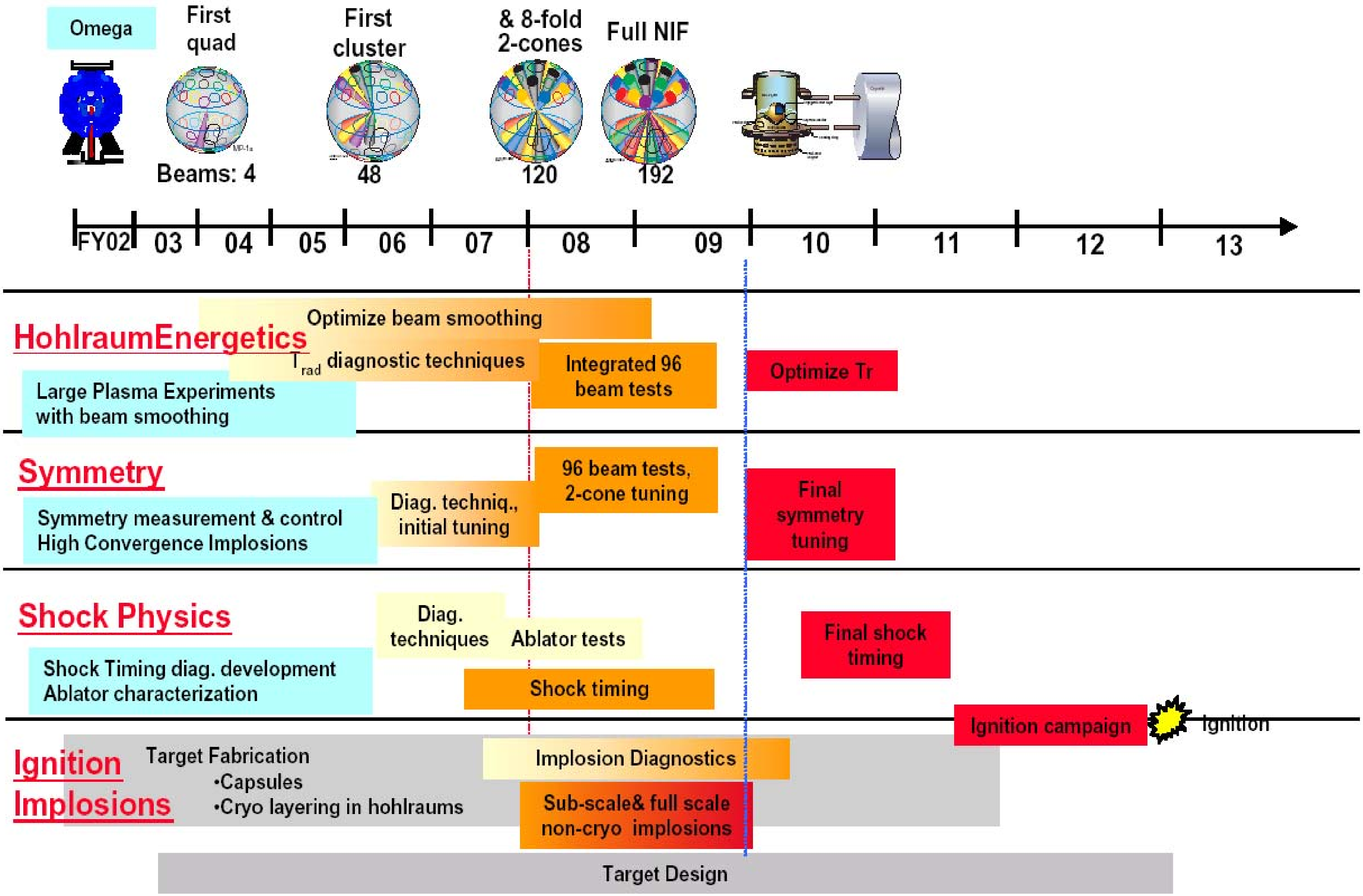


After J. Lindl et. al., 1995, <u>Physics of Plasmas,</u> Vol. <u>2</u>, No. 11, p. 3933

Progress in magnetic fusion



ICF – indirect drive: ignition plan on NIF


Omega

First quad

Beams: 4

First cluster

48

& 8-fold 2-cones

120

Full NIF

192

FY02 03 04 05 06 07 08 09 10 11 12 13

HohlraumEnergetics

Optimize beam smoothing

T_{rad} diagnostic techniques

Large Plasma Experiments with beam smoothing

Integrated 96 beam tests

Optimize Tr

Symmetry

Symmetry measurement & control
High Convergence Implosions

Diag. techniq., initial tuning

96 beam tests, 2-cone tuning

Final symmetry tuning

Shock Physics

Shock Timing diag. development
Ablator characterization

Diag. techniques

Ablator tests

Shock timing

Final shock timing

Ignition campaign

Ignition

Ignition Implosions

Target Fabrication
- Capsules
- Cryo layering in hohlraums

Implosion Diagnostics

Sub-scale& full scale non-cryo implosions

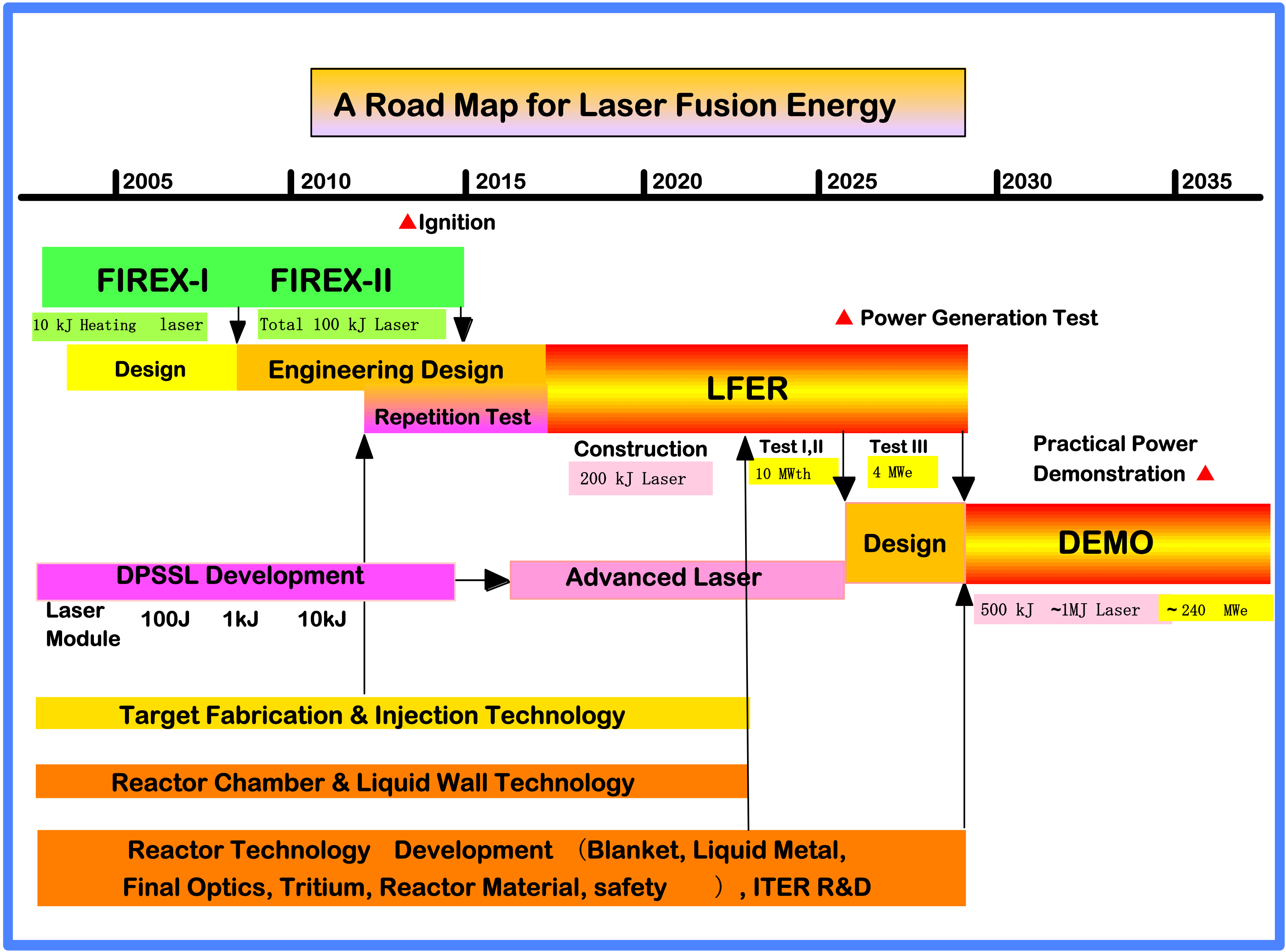
Target Design

Hope from fast ignition
roadmap towards a reactor in Japan

Taken from

Ken Tomabechi [1)]
Yasuji Kozaki [2)]

1) IFE Forum
2) Institute of Laser Engineering, Osaka University



A Road Map for Laser Fusion Energy

2005 2010 2015 2020 2025 2030 2035

▲Ignition

FIREX-I **FIREX-II**

10 kJ Heating laser

Total 100 kJ Laser

▲ Power Generation Test

Design

Engineering Design

Repetition Test

LFER

Construction

200 kJ Laser

Test I,II

10 MWth

Test III

4 MWe

Practical Power Demonstration ▲

Design

DEMO

500 kJ ~1MJ Laser

~240 MWe

DPSSL Development

Advanced Laser

Laser Module 100J 1kJ 10kJ

Target Fabrication & Injection Technology

Reactor Chamber & Liquid Wall Technology

Reactor Technology Development （Blanket, Liquid Metal, Final Optics, Tritium, Reactor Material, safety ）, ITER R&D

ICF systems under development

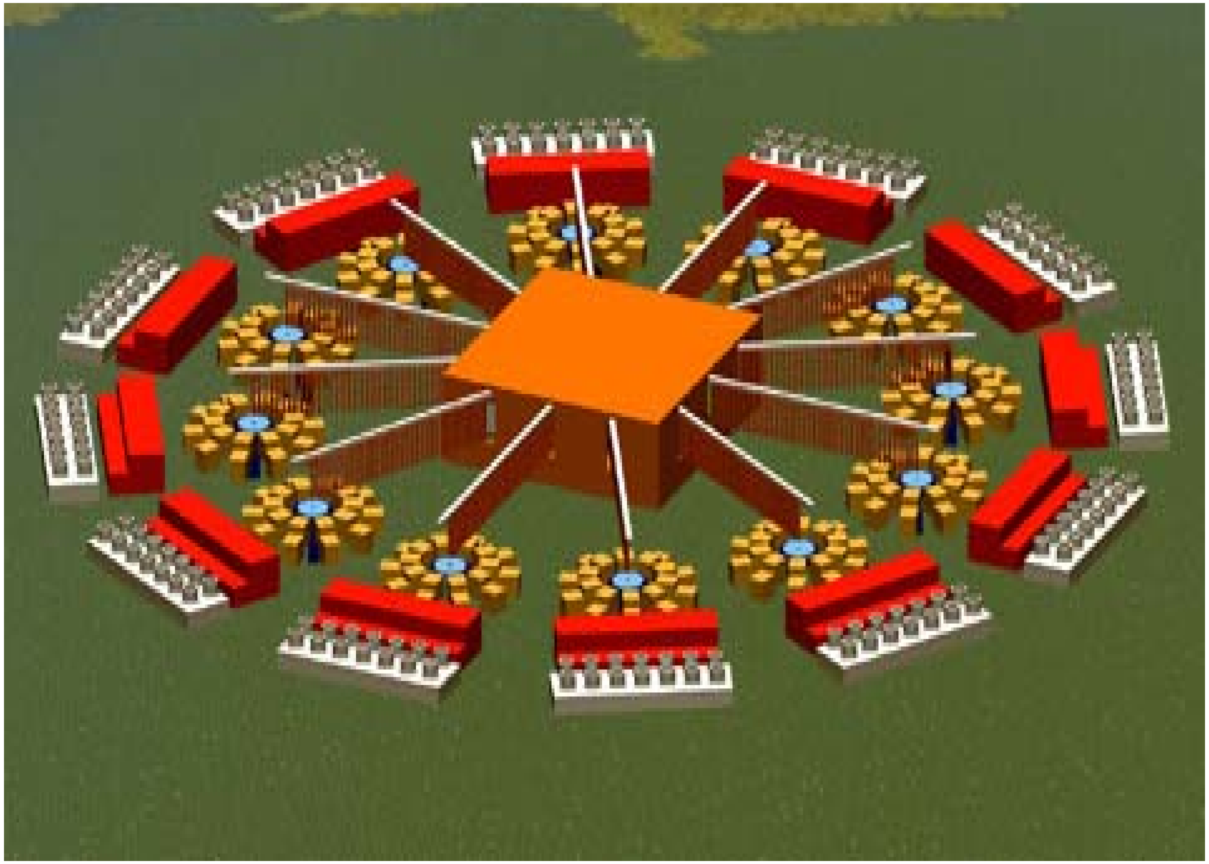
Table 1:
List of Major ICF Driver Facilities
and Their Operating Parameters
(Table Includes both Operating and Planned Facilities)

Location	**Driver**	**Operating Parameters**	**Neutron Production per Shot**
Sandia National Laboratory (USA)	PBFA-II (light ion beam)	36 Beams 100 TW (design) 10 TW (actual)	Unknown
Sandia National Laboratory (USA)	Z-pinch	2 MJ 290 TW 140 eV	D-T target not used yet.
Sandia National Laboratory (USA)	X-1 (successor to z-pinch) (Conceptual Design)	16 MJ 1000 TW	Projection Unknown
Europe	Heavy Ion Design for Ignition Facility (HIDIF) (Conceptual Design)	48 Beams 1 MJ 27 TW	Projection Unknown
Lawrence Livermore National Laboratory (USA)	NOVA laser	10 Beams ~40-70 kJ ~100 TW	10^8-3.6×10^{13}
Lawrence Livermore National Laboratory (USA)	National Ignition Facility (NIF)	192 Beams 1.8 MJ ~360 TW	10^{19} (projected at max 20 MJ yield scenario)
Osaka (Japan)	GEKKO-XII	12 Beams 15-30 kJ 0.1-10 ns	10^{13}
Osaka (Japan)	Kongoh (Under Design)	92 Beams 300 kJ 100 TW	?
Bordeaux (France)	Laser Mégajoule	1.8 MJs 120 TW	Same range as NIF
VNIIEP (Russia)	Iskra-5	12 Beams 15 kJ 0.25 ns	?

Sources: Schirmann and Tobin 1996; Gsponer and Hurni 1998; Velarde 1993; Livermore 1996b; Singer 1998.

Long term development of z-pinch

The long-range goal of Z-Pinch IFE is to produce an economically-attractive power plant using high-yield z-pinch-driven targets (~3 GJ) at low rep-rate (~0.1 Hz)



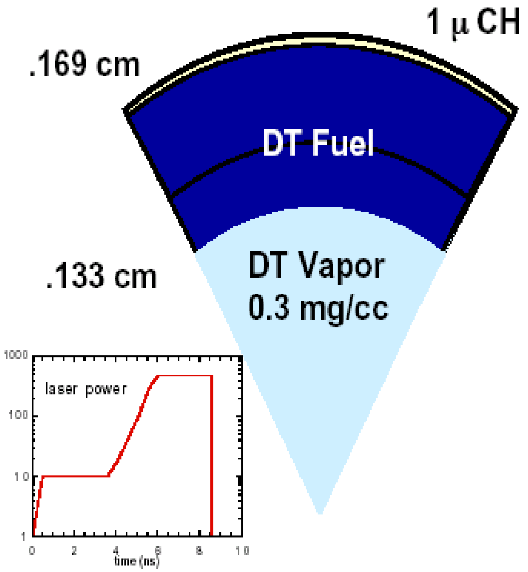
Z-Pinch IFE DEMO (ZP-3, the first study) used 12 chambers, each with 3 GJ at 0.1 Hz, to produce 1000 MWe

Control of hydrodynamic instabilities and laser imprint determine key features of laser direct drive targets

NIF BASELINE

PURE DT

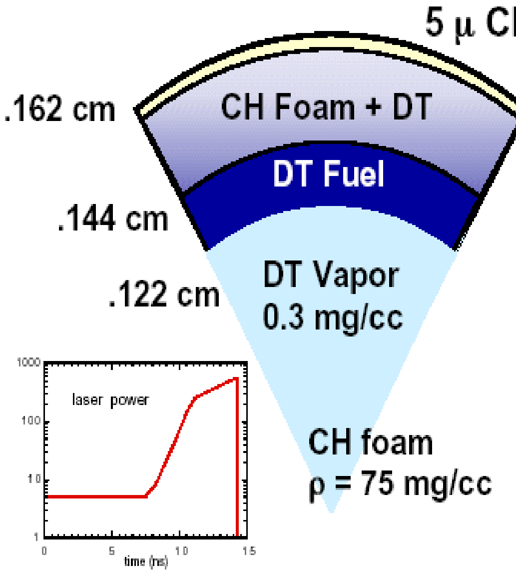
(shock heated)

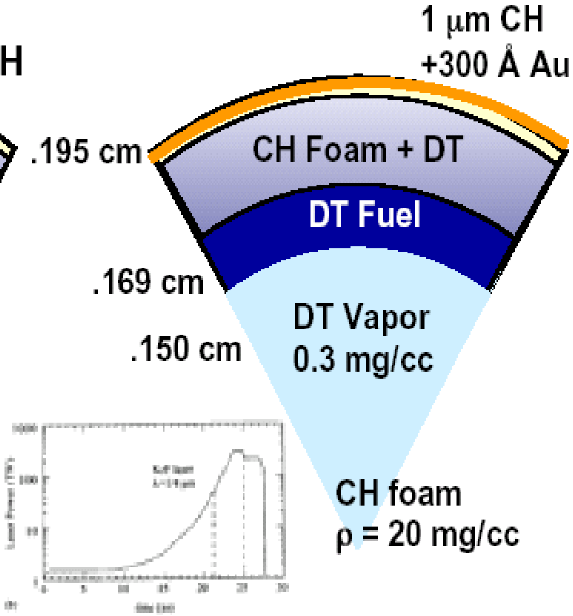


ADVANCED DESIGNS

CH FOAM /DT+ DT

GOLD+ CH FOAM / DT + DT





Laser Type	Glass	Glass	KrF	KrF (ISI)
Laser Energy	1.6 MJ (~60% absorbed)	1.6 MJ (90% absorbed)	1.6 MJ	1.3 MJ
1-D Gain	20-30	50-120	108	127