Everything you always wanted to know about fusion reactors, but were afraid to ask

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Be ware of my plagiarism

- **Everything You Always Wanted to Know About Sex * But Were Afraid to Ask (1972)**
- **Director: Woody Allen**

Plan

- Introduction: The energy issue
- The Physics basis: reactions and fuels
- Why fusion is considered as a “disruptive energy”?
- Some (not all) issues
- ITER
- Technology Road map towards a fusion reactor
- Inertial confinement
- Q&A: Everything you always wanted to know about fusion reactors, **but dare to ask**

Introduction: The energy problem

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- The constraints:

1. Increase of world population and therefore energy needs: 7.3 billions in 2015 to 8.9 billions by 2050, remaining stable beyond (UN study), coupled with a today inequality in energy access (inverse champagne glass)
2. Change in energy mix requirement: stronger reliance on electricity for an increasing urban population
3. Necessity to have "sustainable" energy "***Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland report)***

- Environment aspects: global warming
- Safety: accidents should not impose population evacuation
- Legacy towards next generations: depletion of fossil fuels; waste repository on a "human" (not geological) time scale

Electricity consumption/ capita

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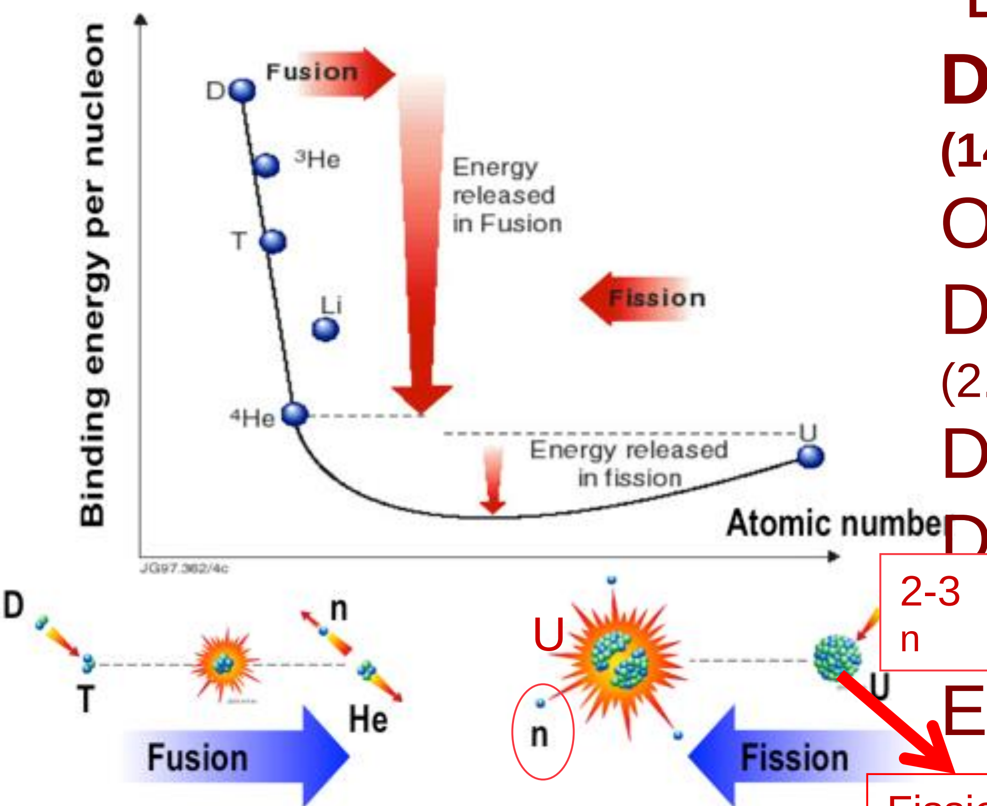
- World bank data (http://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC/countries/all?display=graph)
- World 3064 kWh/capita
- EU: 6144 kW/h/ capita; Germany: 7270 kWh/capita ; Switzerland: 7343 kWh/capita
- China: 3810 kWh/capita; India: 744 kWh/capita
- Vietnam: 1273 kWh/capita, Haiti: 50 kWh/capita→ = 0.007 of Germany

Fusion reactions



Fission products

"Easiest" to achieve reaction:

D + T→ He (3.5 MeV) + neutron (14.1 MeV)

Other reactions

D + D → He^3 (0.82 MeV) + neutron (2.45 MeV

D + D → T (1.0MeV) + H (3.0MeV)

D + He^3→ He^4 (3.76 MeV) +p (14.7MeV)

Energy release $E = \Delta m * c^2$

*"Fusion will bring a disruption in the way we view energy" (Newsletter of WEC, Daegu 2013)

Fusion cross section

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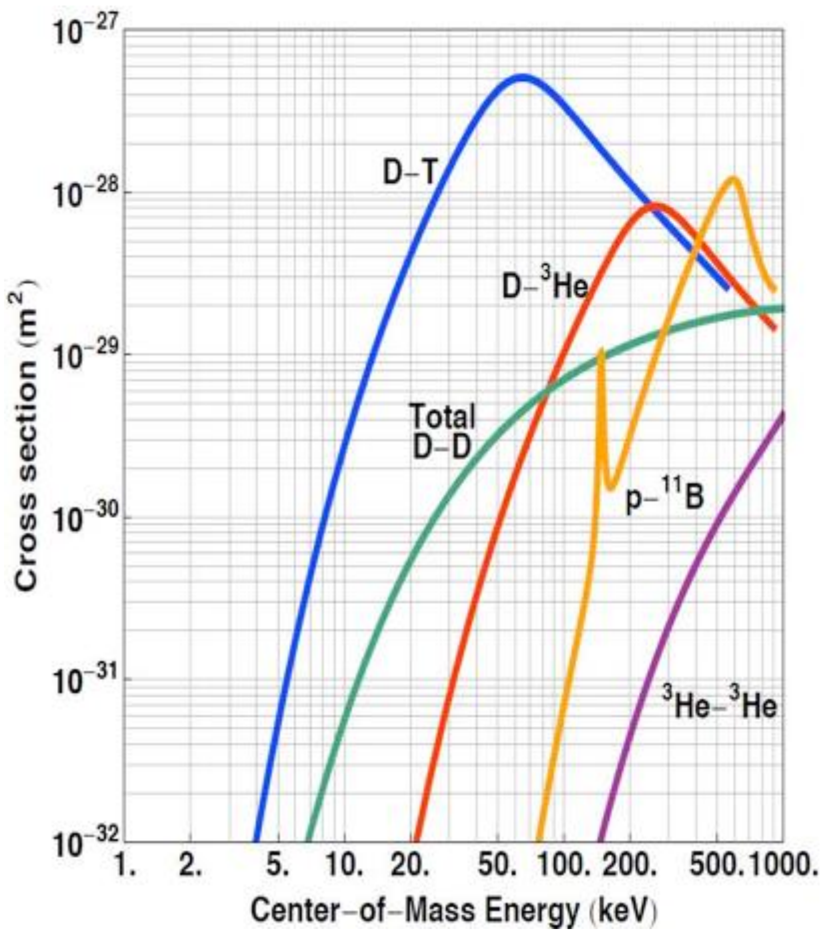
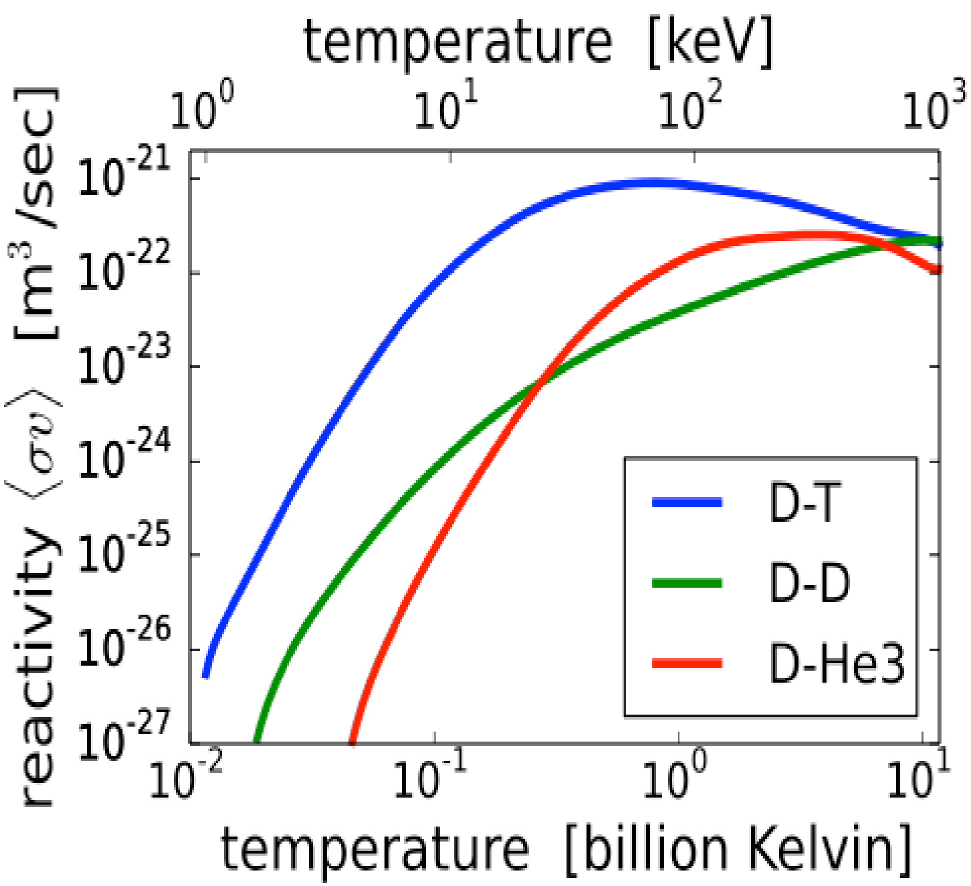
1 keV → T = 10 millions degrees through the relation
$k_B T = E$



Lawson criterion (1)

- Fusion pow
- Ions have a characteriz
- Calculation which is average ov
- Triple prod Energy confinemer



Derivation of Lawson criterion

$$P_{fusion} = n_D n_T \langle \sigma v \rangle \mathcal{E}_{fusion}$$
$$= \frac{n^2}{4} \langle \sigma v \rangle \mathcal{E}_{fusion}$$

Plasma energy: $W = \int 3 n k_B T \, dV$
$$= 3 \overline{n k_B T} \, V$$

$$P_L = \frac{W}{\tau_E} = P_{Heating}$$

Equate $P_{fusion} = P_L = P_{Heating}$

$P_{Heating}$ = External Heating + P_α

$$P_\alpha = \int \frac{1}{4} n^2 \langle \sigma v \rangle \mathcal{E}_\alpha \, dV$$
$$= \frac{1}{4} \overline{n^2 \langle \sigma v \rangle} \mathcal{E}_\alpha V$$

Derivation of Lawson criterion

Lawson criteria

$$P_{ext.\ heating} = \left[\frac{3 n T k_B}{\tau_E} - \frac{1}{4} n^2 \langle \sigma v \rangle \mathcal{E}_\alpha \right] V$$

$$n \tau_E > \frac{12}{\langle \sigma v \rangle} \frac{k_B T}{\mathcal{E}_\alpha}$$

$$\langle \sigma v \rangle \approx 1.1 \cdot 10^{-24} T^2 \quad m^3 s^{-1}, \; T = keV$$

$\Rightarrow$ Triple product $nT \approx$

with T in keV.

Lawson criterion (2)

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- Q definition= Fusion power/ External Heating power
- But the fusion reactions provide energetic He ions (3.5 MeV) which can thermalize with the D and T ions (10-20 keV): He ions is a source of heating
- Q→ infinity (ignition) if External Heating power is null: all needed heating is provided by He ions
- For a reactor, ignition is not required Q = 30-40

The challenge of fusion

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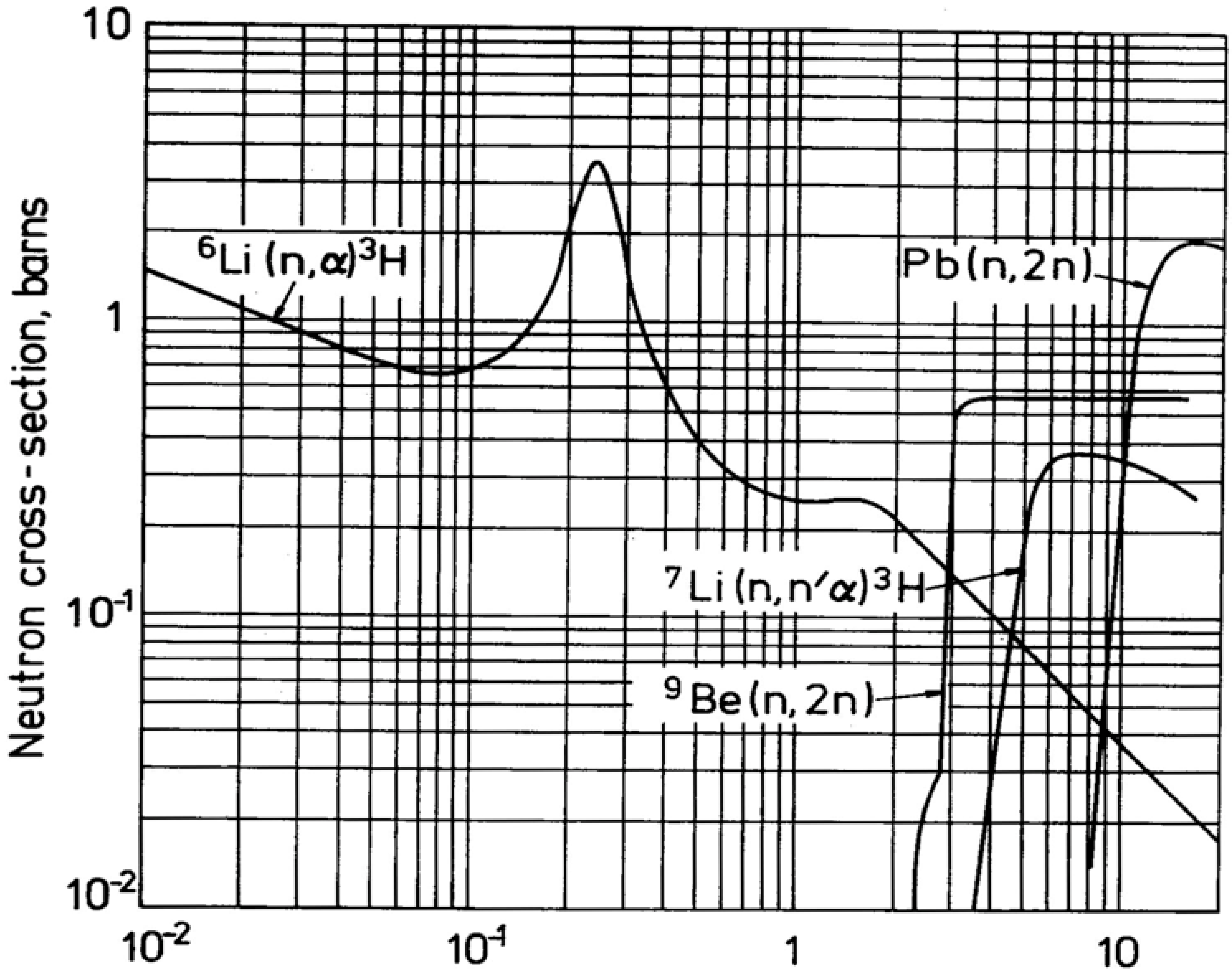
Density **n*** Temperature **T***Energy confinement time $\boldsymbol{\tau_E} >$ 5* 10^{21} m^{-3}keV s

The challenge:

1. To create a plasma with n about 10^{20} m^{-3} and T about 10^8K, i.e. 10 keV
2. To confine its energy during τ_E of a few seconds

There are many time scale: Particle confinement time τ_P, Plasma duration, Energy confinement time

Fuel issues



- D: ab
- T: Sh
  abou
- Need
  the fu

^{6}Li + n –

^{7}Li + n –

- Impo … r

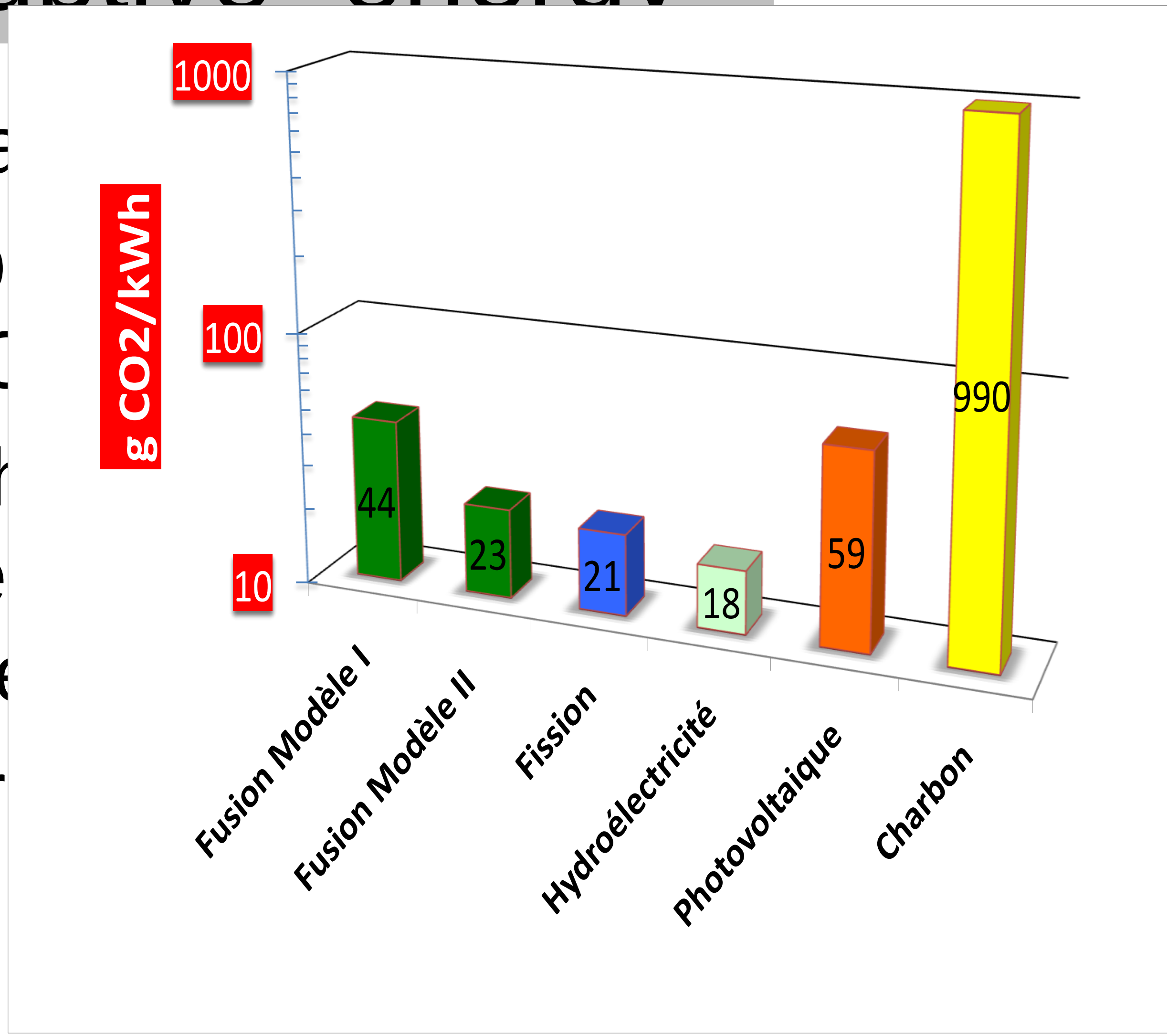
Fusion : a “disruptive” energy

- Why a

Li is ab ... a water (WEC

2) No ch ... nts: fuel inside ... ew minute ... t);

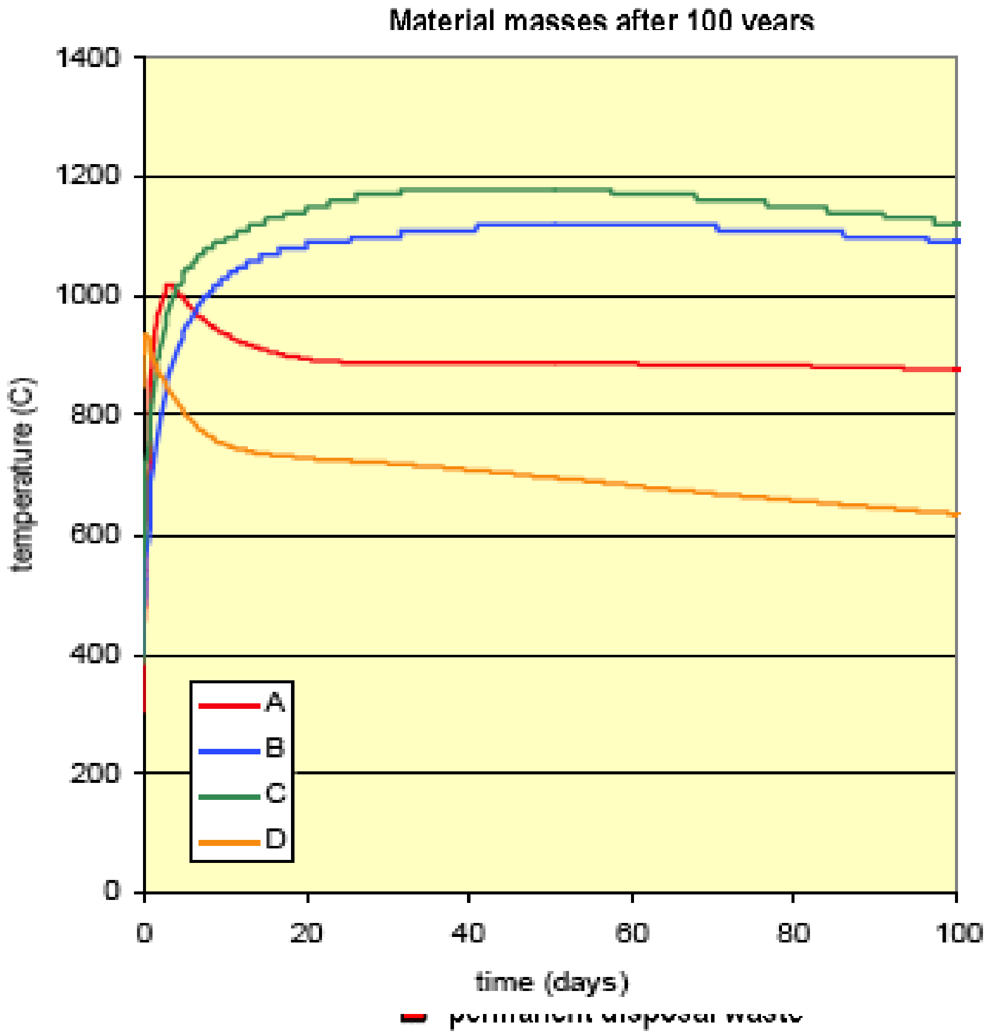
3) Envir



Fusion : a “disruptive” energy

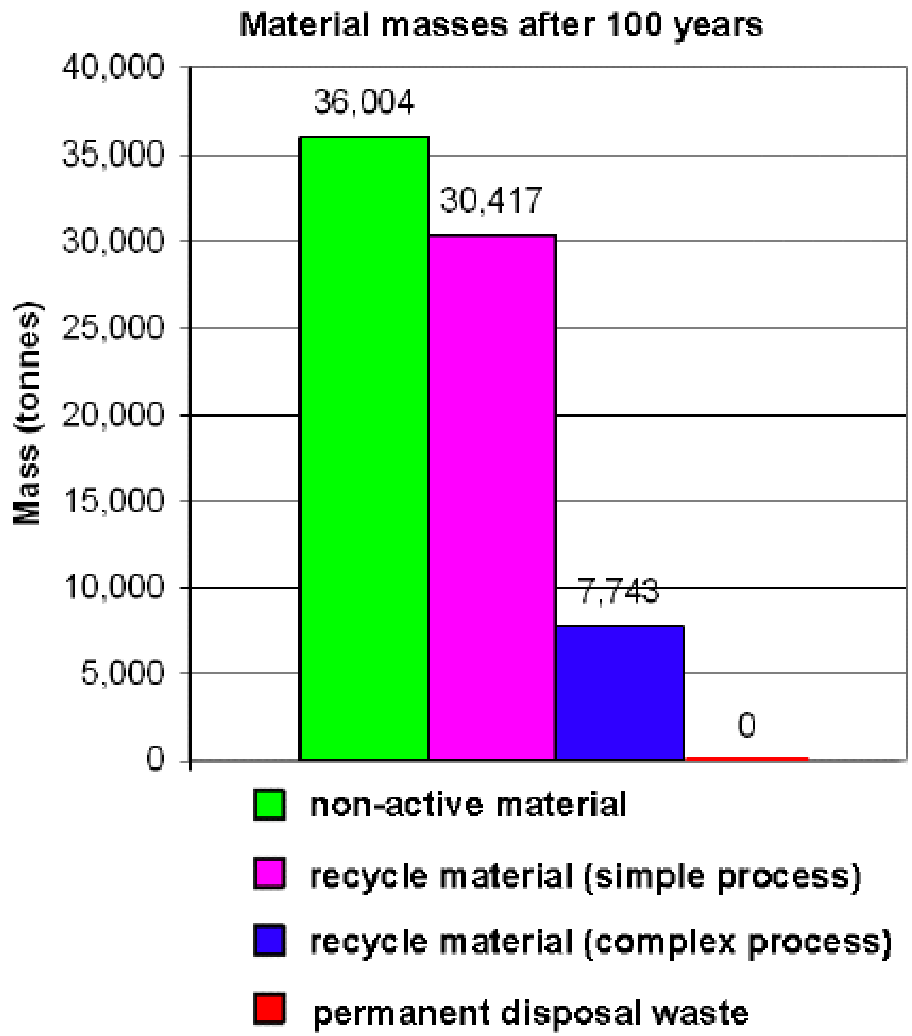
4. Develc ... ls (Cf. Talk by ... no need c

5. This cc ... spect by red



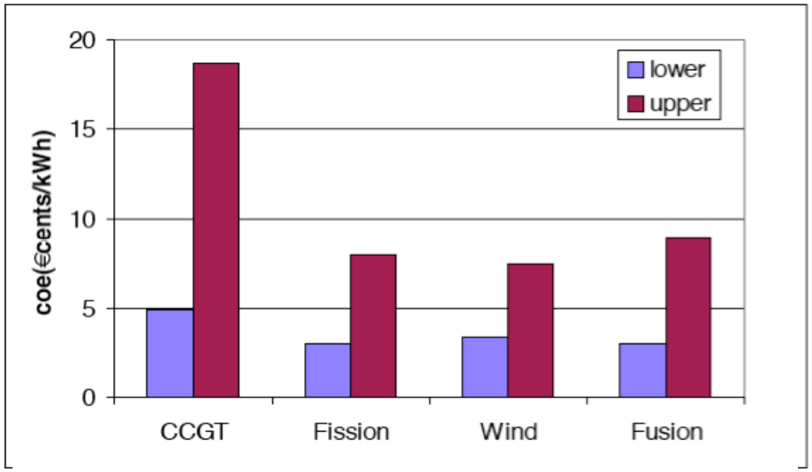
Waste disposal

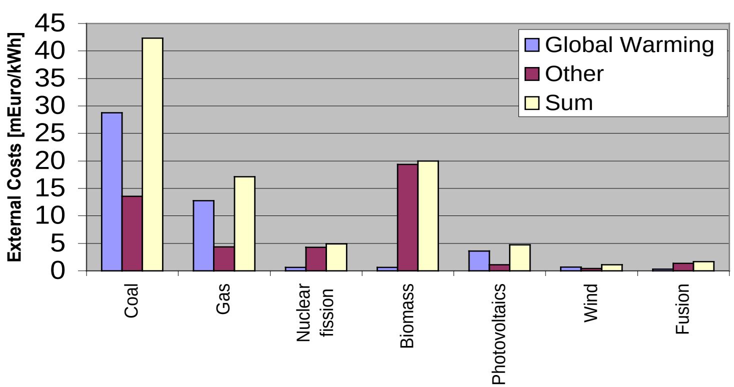
- Need al
- What

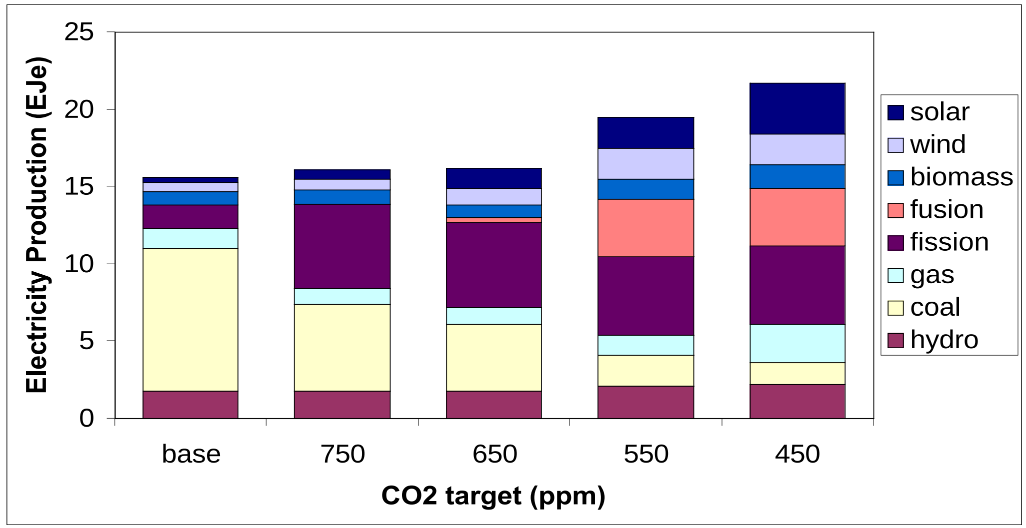


Market penetration

- Economics studies confirm the possibility for fusion to penetrate the market







State of matter at T> 10^5K , about 10 eV

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- Binding energy e-ion: about 10 eV
- At fusion temperature, the state of matter is plasma, i.e. a “gas” formed by electrons and ions , globally neutral and dominated by “collective” effect
- Debye shielding: a charge is surrounded by a cloud of opposite charges which “shield” its Coulombian potential V_c. Beyond a few Debye lengths λ_D, V_c is no longer felt. $\lambda_D = (\varepsilon_0 k_B T/n_0 e^2)^{1/2}$

Confinement

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- Due to the Debye screening, electrostatic confinement is not possible: electric field is shielded after a few Debye length
- Two possibilities:

◆No confinement→ **Inertial confinement** and realisation of the triple product through very high density n (very short τ_E and τ_P)

◆By magnetic field → Magnetic confinement

Magnetic confinement (1)

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- Through the Lorentz force $F_{lorentz} = q(\underline{v} \times \underline{B})$
- $\underline{B}$ is generated either or both current by external coils or by the plasma it self

$$\underline{\nabla} \times \underline{B} = m_o \underline{j}$$

$$\underline{f} = \text{Force density in fluid description}$$

$$= r_{el} \left(\underline{j} \times \underline{B} \right)$$

Magnetic confinement (2)

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- Simple toroidal magnetic field (closed field lines) created by a a wire is not sufficient : particles "drift" across magnetic field due to curvature and spatial variation (1/r) of B: the drift direction (vertical) depends on the charge, leading to charge separation and hence a vertical electric field E. This E combined with the B leads to a global drift of both charge species according to (E x B), leading to loss of confinement

Tokamak

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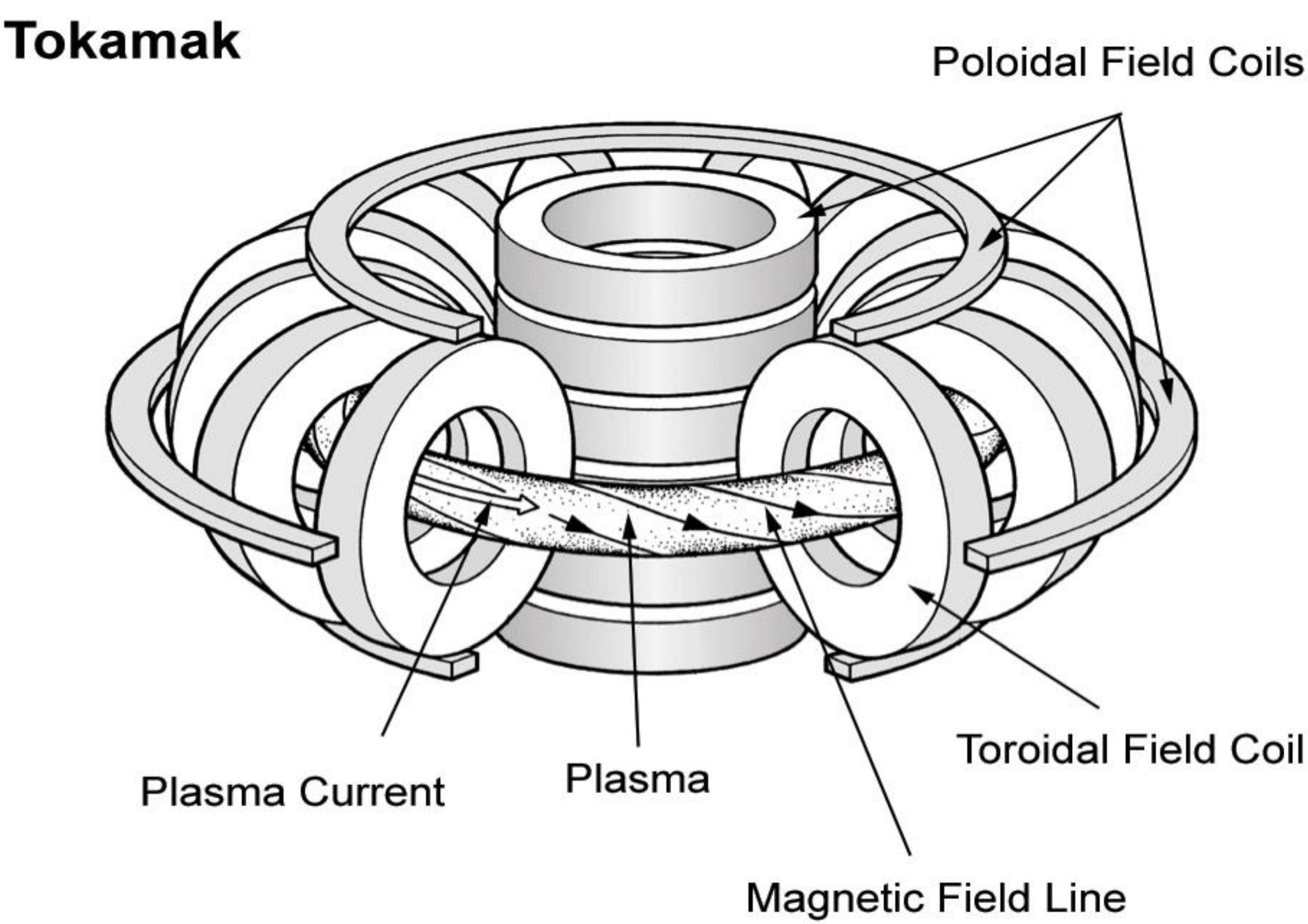
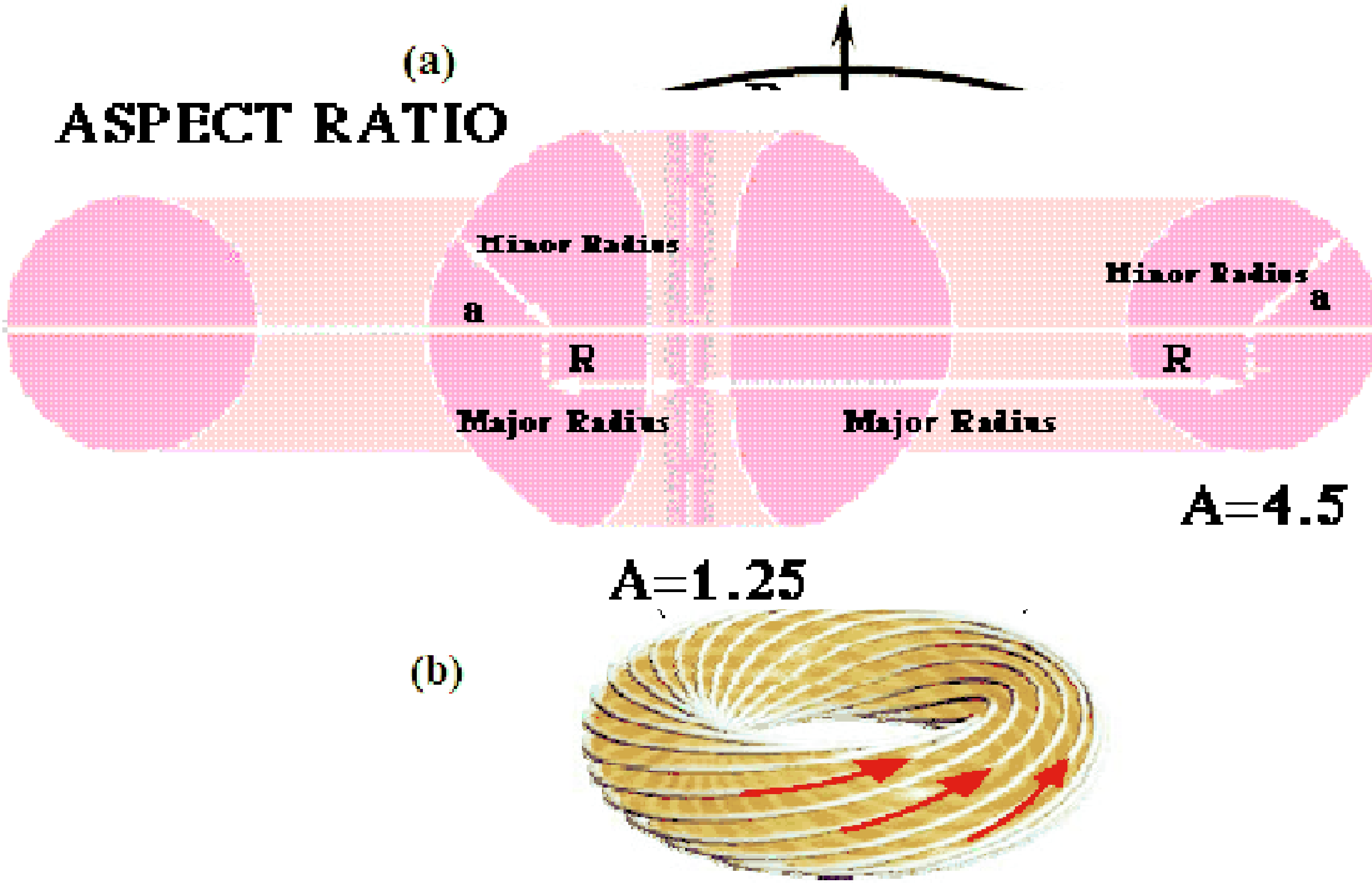
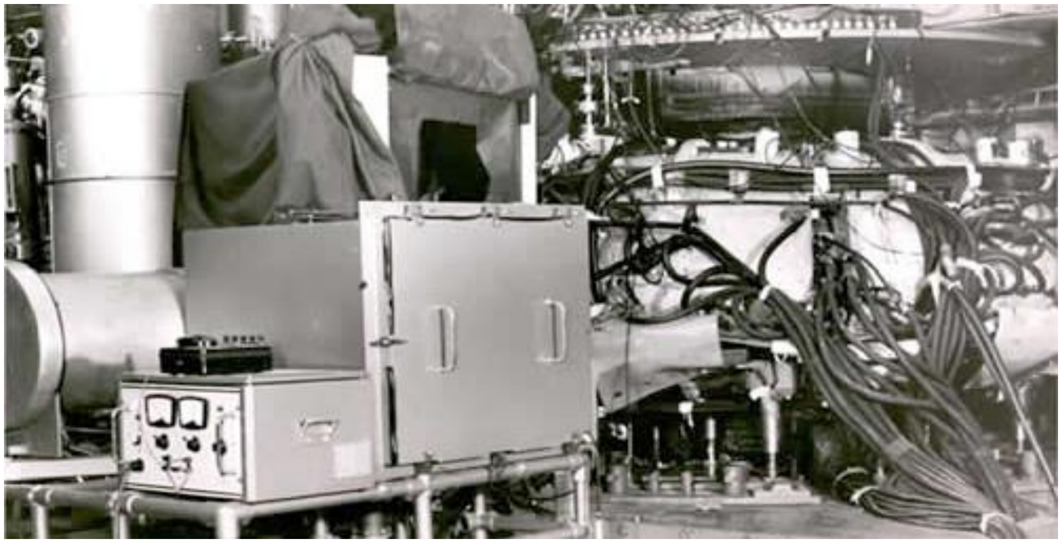
  fi …
  c … tself
  I_P …



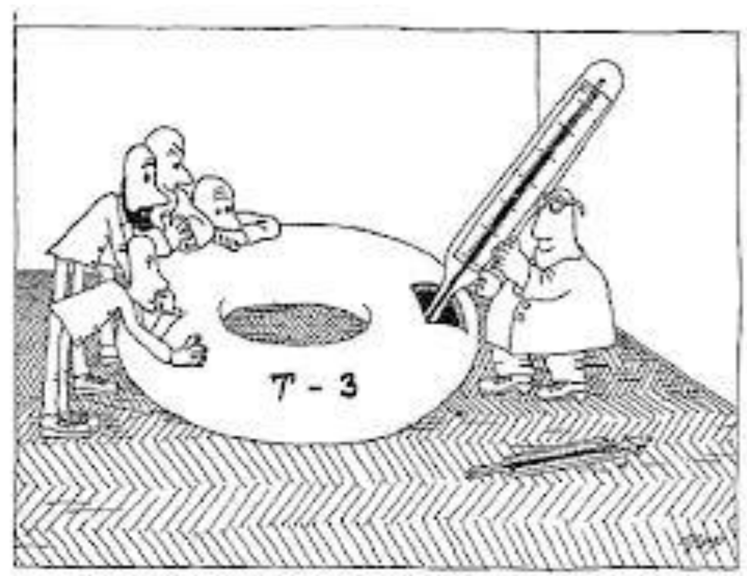
Tokamak field lines and aspect ratio



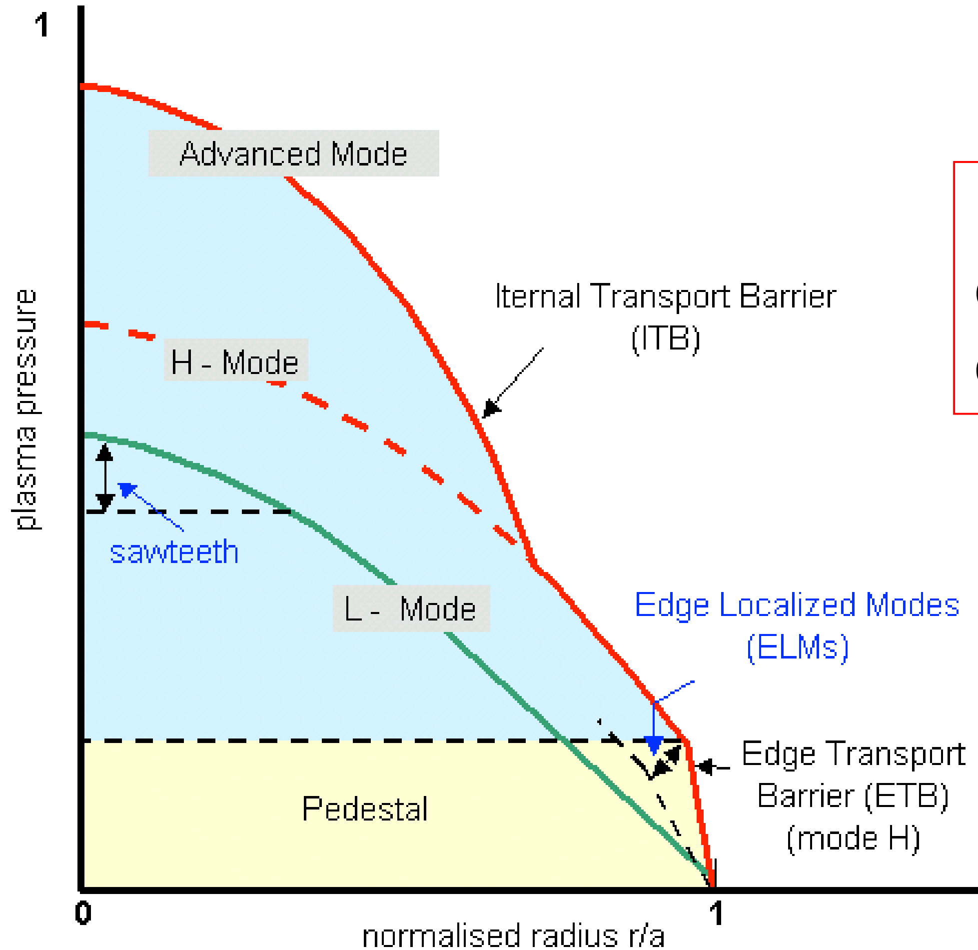
T3 (USSR)



1968: 1 keV confirmed by a team of scientists from UKAEA (cold war). It opens the era of tokamak



Confinement modes



H mode: High energy confinement mode

H→ L mode transition

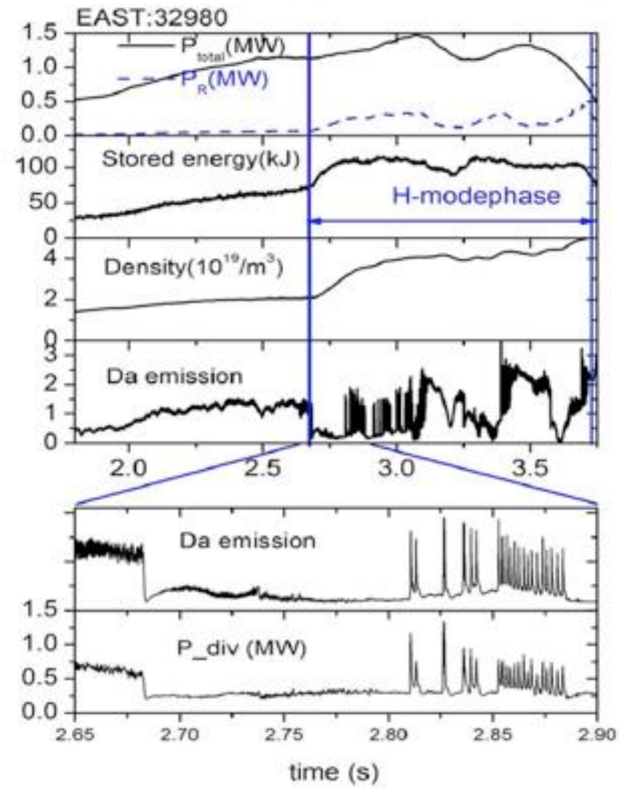
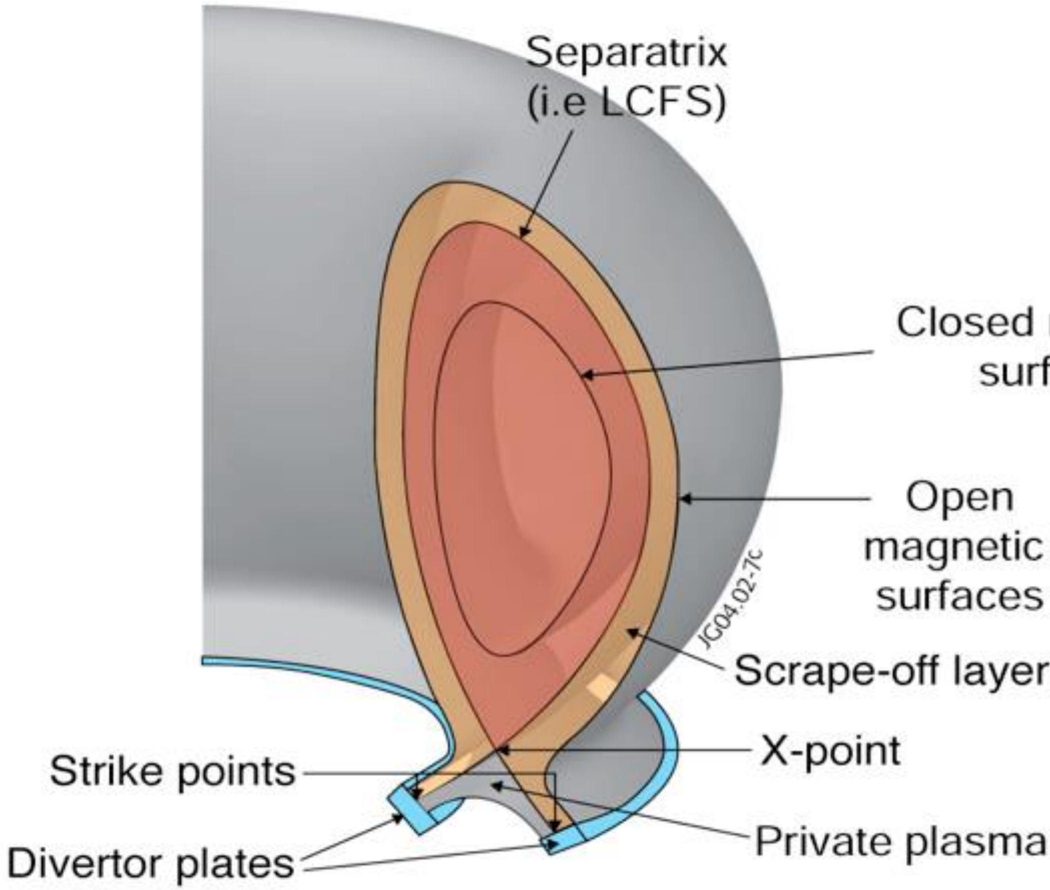


Fig.1 A typical LH driven H-mode discharge with Ip=0.6MA, BT =1.55T, PLHWinj =1MW. The total absorption power prior to the L-H transition is about 1.5 times the empirical L-H transition threshold power scaling. H89~1.5 or HIPB98,y2~0.9.

Divertor



Divertor: Where particle and energy from the plasma are removed.
Divertor plate: W
A high heat flux material

Divertor (ITER)

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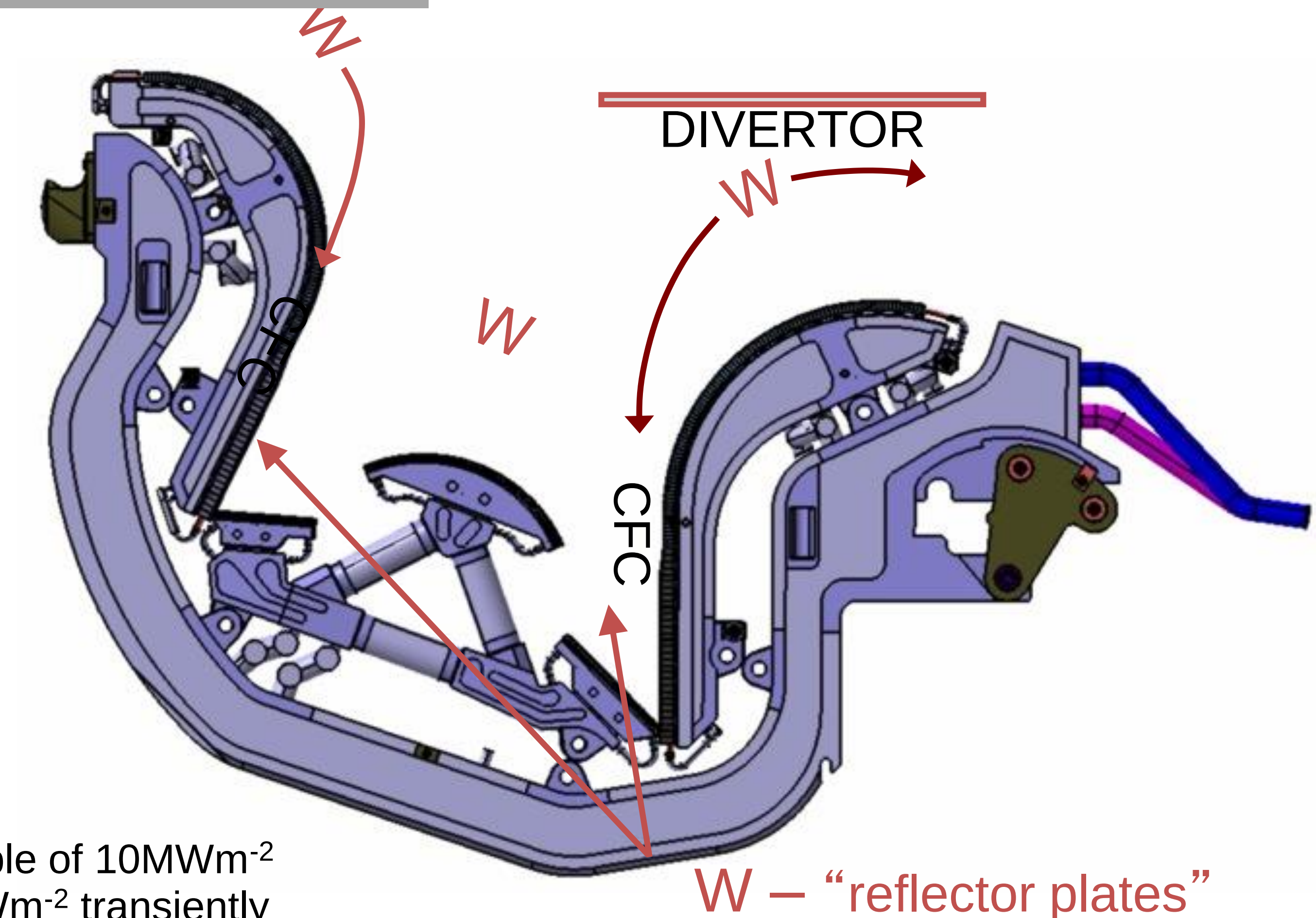
Heat load up
to 20 MW m^{-2}



Divertor:

- 54 Divertor cassettes
- High heat flux components capable of $10 MWm^{-2}$ in stationary operation and $20 MWm^{-2}$ transiently

Divertor (ITER)

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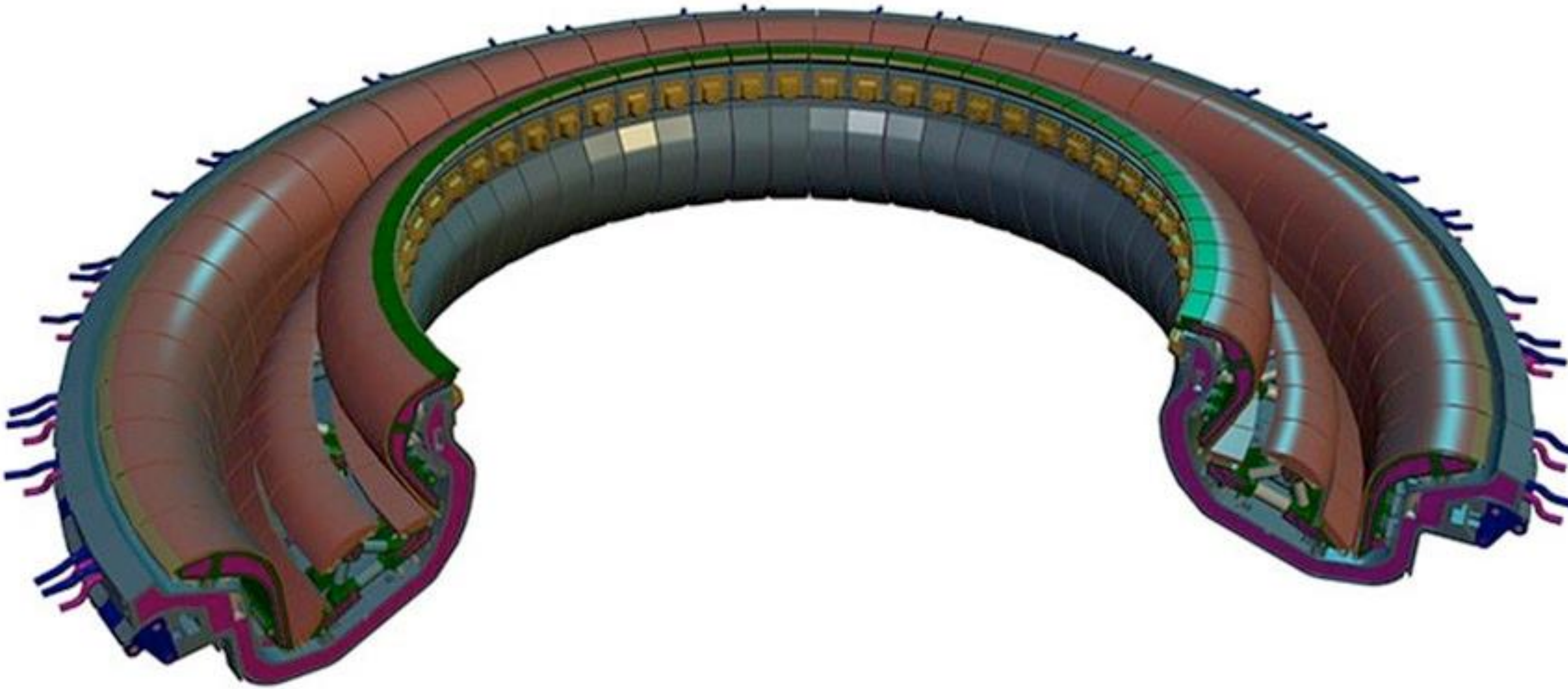

Stellarator

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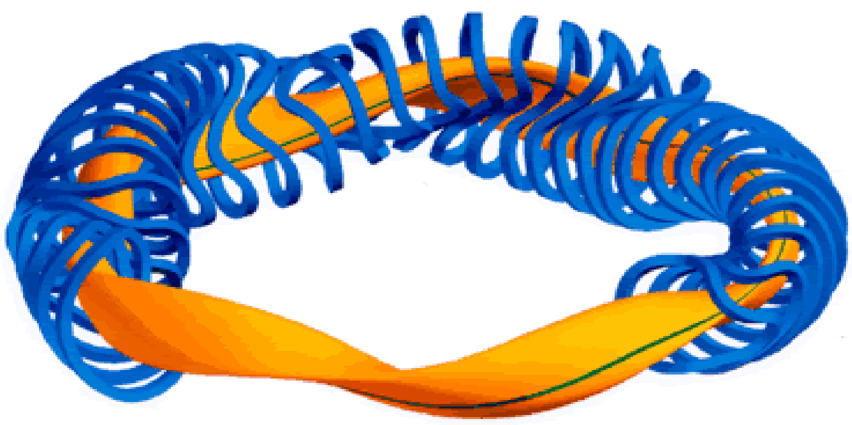
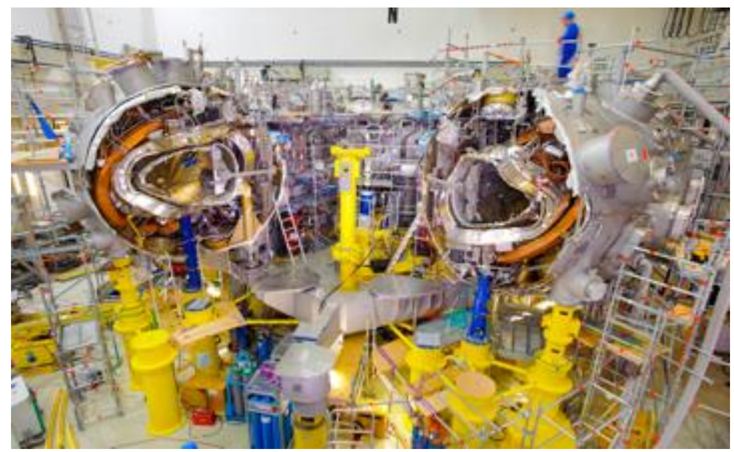
- 3D magnetic confinement created exclusively by external magnetic coils. No plasma current: no disruption





W7 X stellarator

Heating (1)

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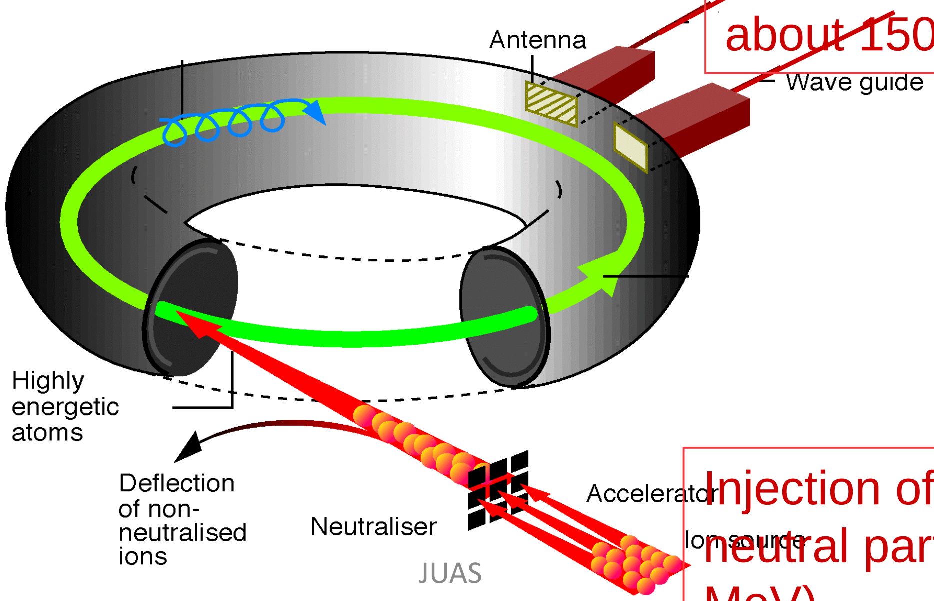
- In the case of a tokamak where we have a plasma current I_P, what is the heating by this current?
- What is the resistivity of a plasma? In the keV regime, it is like Cu, but it decreases as $T^{-3/2}$.
- Ohmic heating , taking into account phenomenological loss rate, cannot bring a tokamak plasma to the 10-20 keV regime. The temperature will be about 4 keV (Freiberg)

Heating (2)

- Heating by absorption RF waves or by injection of fast neutral particles, which thermalize with the plasma particles

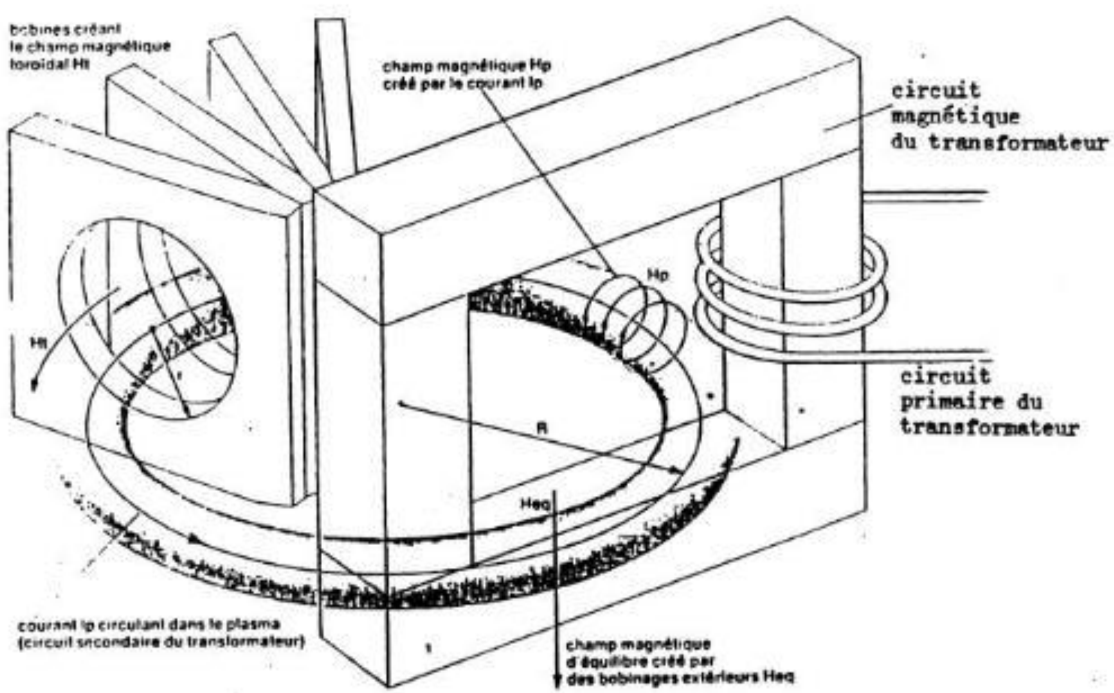
RF waves at ion cyclotron frequency(about 50 MHz) or electron cyclotron frequency (about 150-200 GHz)



Injection of fas t neutral partciles (1 MeV)

Current drive (1)

- What is current drive? The toroidal plasma I_P is an essential component of a tokamak



I_P is induced as the current in a transformer. So it cannot be sustained in steady state

Current drive (2)

- N
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k
[
c
r
- E
r

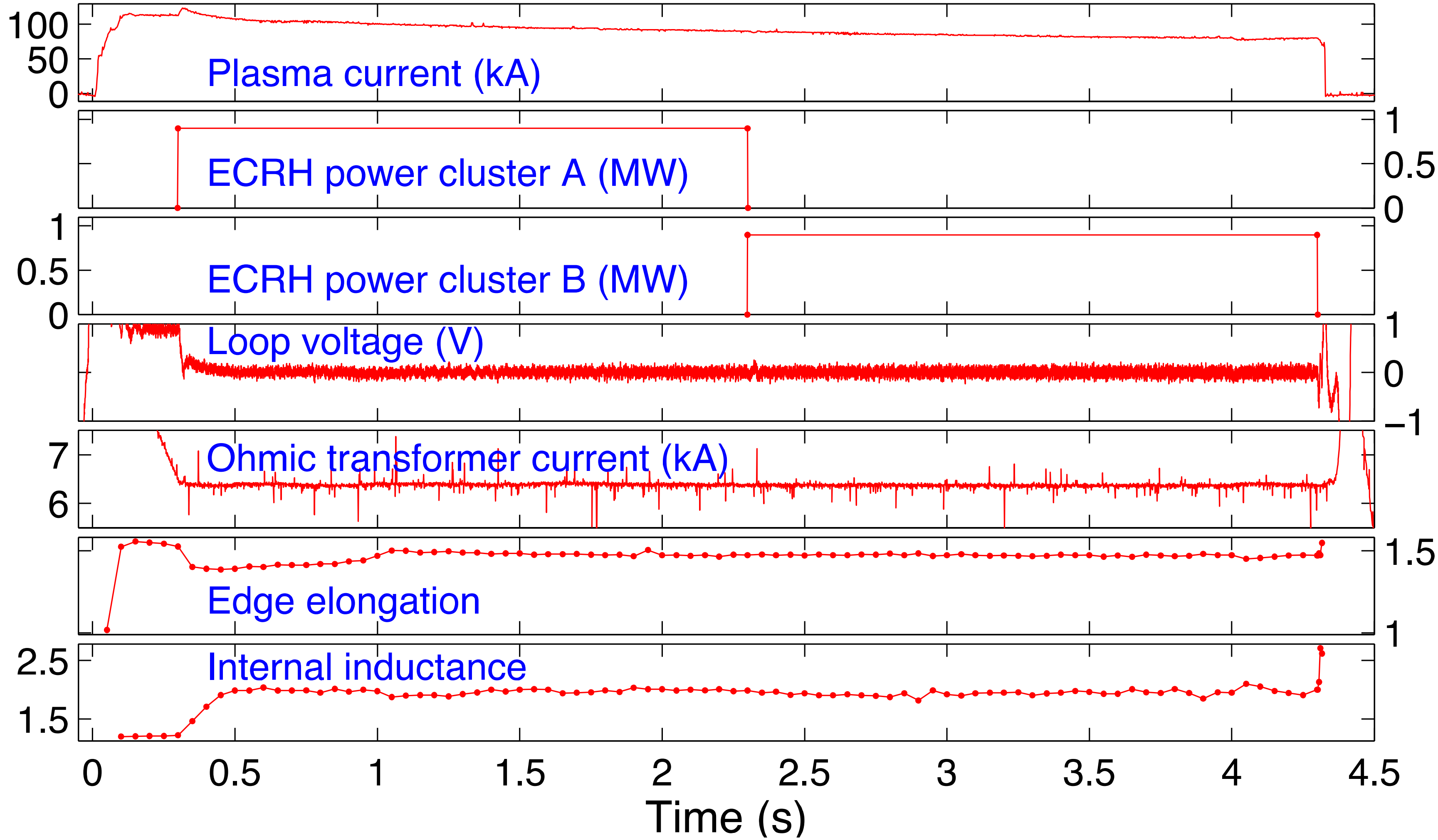

FIG. 1. TCV discharge 20881 of record length (4.3 s), sustained by 0.9 MW ECCD.

Physics issues (1)

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- A magnetically confined plasma contains free energy which can be released as instabilities
- Example: Consider a tokamak as a levitated ringin a magnetic field topology. Eanrshaw theorem indicates that the equilibrium is not stable. One degree of freedom is unstable: in a tokamak it is called the Vertical Displacement Event VDE, leading , if uncontrolled to disruption

Physics issues (2)

- Another example: The confinement of the 3.5 MeV He ions produced by the fusion reactions
- These energetic ions may be lost by interaction with waves (Alfven waves) excited in the plasma, before thermalizing with the D and T ions.
- Heat removal in divertor
- …. And many more

Material science issues

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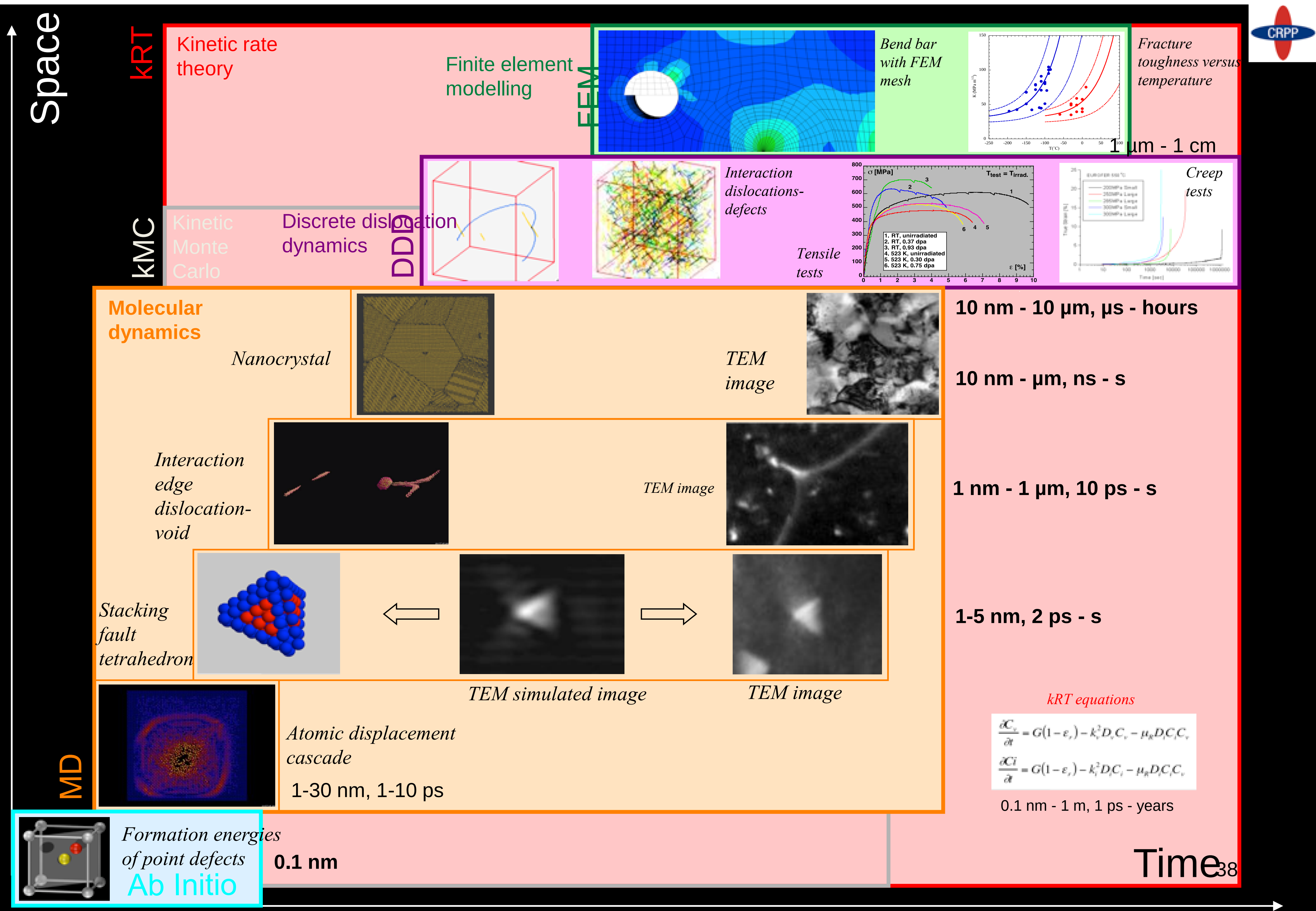
- A very exciting field to deliver materials which

✓ Have the necessary thermo-mechanical properties under irradiation

✓ Are compatible with the operation of magnetically confined plasma

✓ Fulfil the promises of waste disposal

✓ But how to test the material under 14 MeV neutrons?



$$\frac{\partial C_v}{\partial t} = G(1-\varepsilon_r) - k_v^2 D_v C_v - \mu_R D_i C_i C_v$$

$$\frac{\partial C_i}{\partial t} = G(1-\varepsilon_r) - k_i^2 D_i C_i - \mu_R D_i C_i C_v$$

14 MeV effects

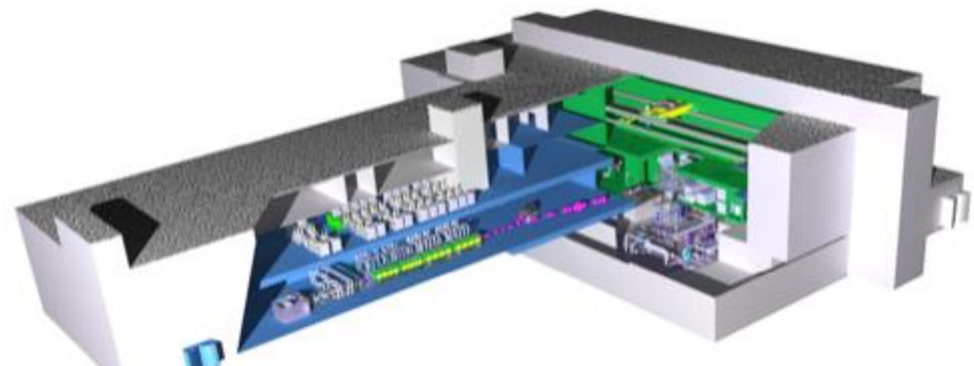
- Neutrons can cause mechanical defects (Frenkel pairs: creation of an instertitial and vacancy)
- But 14 MeV can also cause production of He and H
- $^{56}Fe(n,\alpha)^{53}Cr$ (incident n threshold at **2.9 MeV**)
- $^{56}Fe(n, p)^{56}Mn$ (incident n threshold at **0.9 MeV**
- He and H can cause swelling and embrittlement

Early (Fusion) Neutron Source

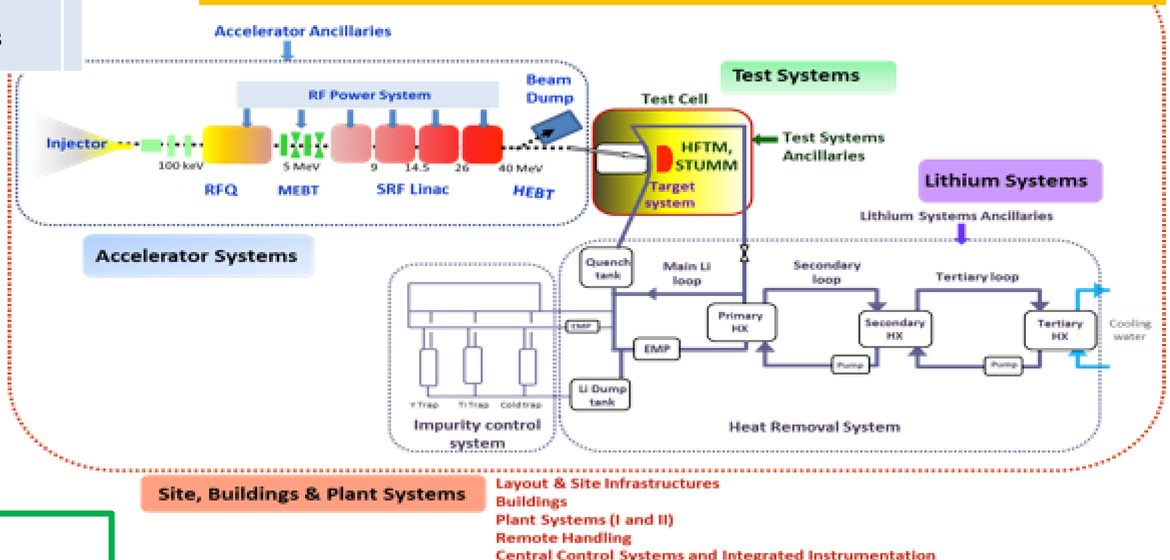
- Develop the engineering design of the IFMIF-DONES (DEMO Oriented Neutron Source) facility.

	IFMIF	IFMIF-DONES
Beam current	2 x 125 mA (Li target)	1 x 125 mA (Li target)
Beam energy	40 MeV	40 MeV
Neutron production	10^{18} n/s	5 x 10^{17} n/s
Typical Damage Rate	40 dpa/fpy @>60cm³ + 20 dpa/fpy @>400cm³	20 dpa/fpy @>60 cm³ + 10 dpa/fpy @>400 cm³

IFMIF-DONES preliminary conceptual design



IFMIF-DONES Plant Configuration



This will be the starting point of our project
The design will be updated and further developed!!!

=> Courtesy: A. Ibarra and WPENS Team

ITER objectives (1)

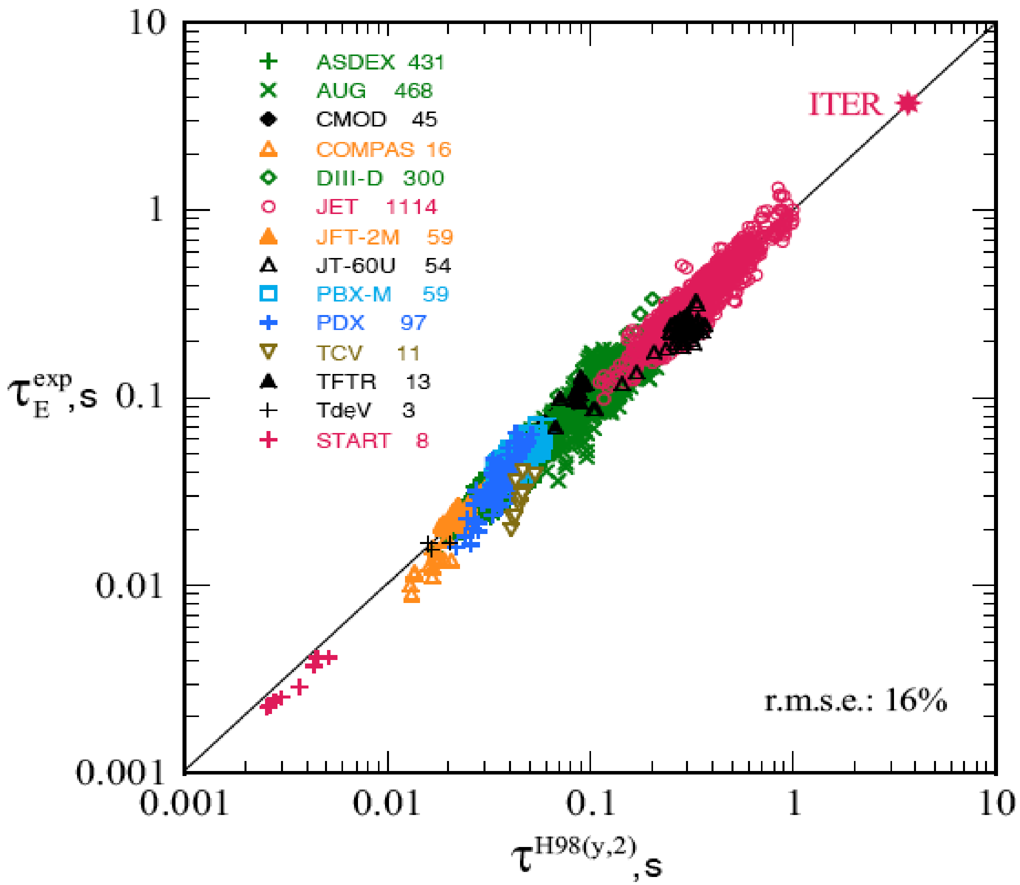
- ITER objectives:

1. Produce P_{fusion} = 500 (360) MW_{th} of during 400 (3000) s with an external additional heating $P_{heating}$ 50 MW (Power gain $Q = P_{fusion} / P_{heating} = 10$)
2. Study physics of a “burning” plasma, i.e. when the energetic 3.5 MeV He nuclei from fusion reactions are confined and provide a dominant heating power (100 MW compared to the 50 MW of external heating)

ITER objectives (1)

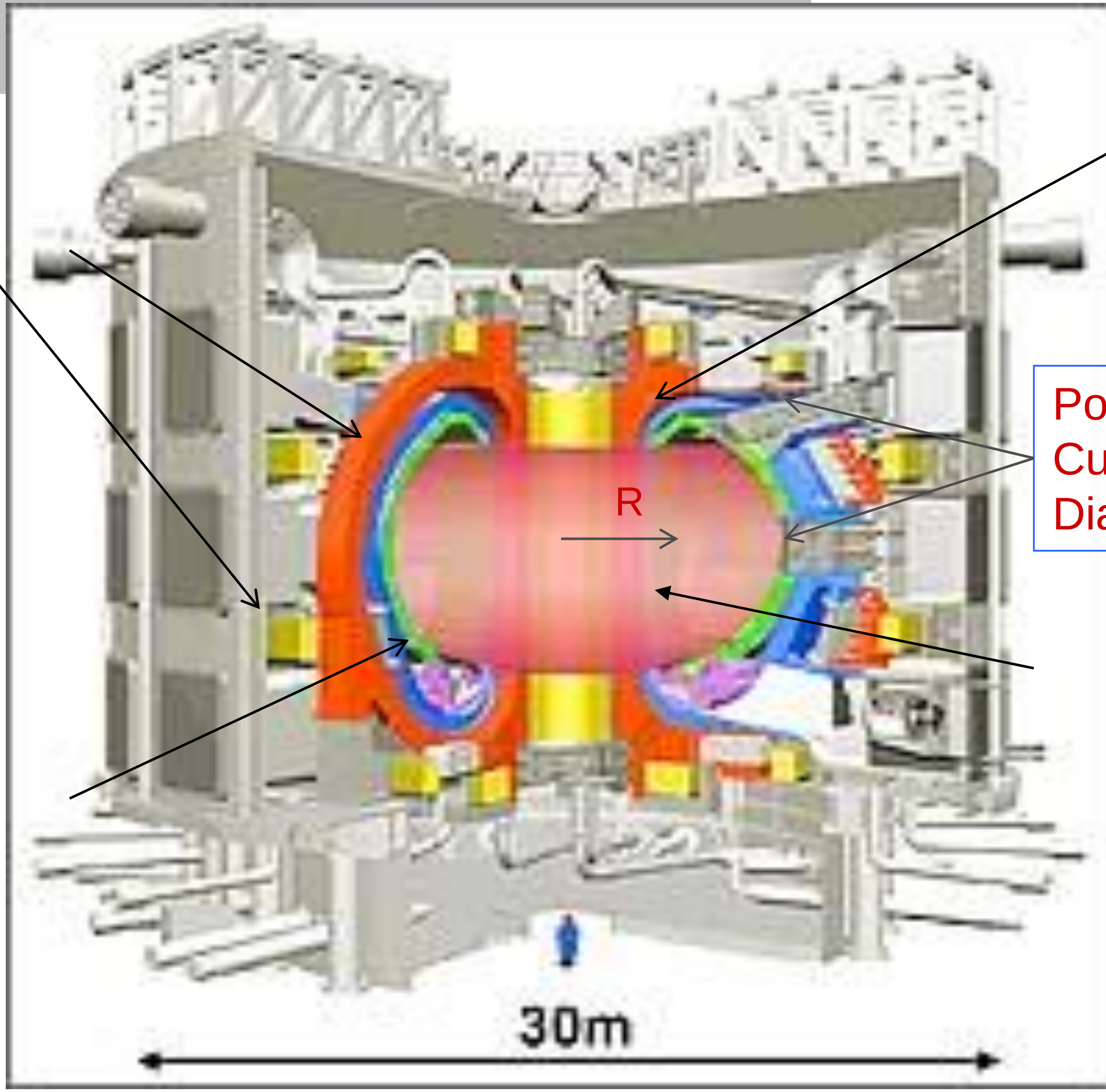
3. Integrate in a single device the different technologies (e.g. superconductivity SC, heating methods and all associated power electronics) and the physics constraints
4. Prove the safety aspects of a fusion reactor: ITER is the first fusion reactor to be licenced as a nuclear reactor

Extrapolation for ITER



$$\tau_E^{H98(y,2)} = 0.0562 I^{0.93} B^{0.15} \bar{n}_{19}^{0.41} P^{-0.69} R^{1.97} \kappa_a^{0.78} \varepsilon^{0.58} M^{0.19}$$

The ITER tokamak



SC Poloidal field (PF) coils

SC Toroidal field (TF) coils
B_T= 5.3 T

SC Central solenoid (CS)
Generates I_P

Ports for Heating & Current Drive and Diagnostics

Plasma
Current I_P :15 MA
Major radius R= 6.2 m
Plasma radius a = 2m
R/a= 3.1
Fusion power: 500 MW
Pulse : 400s

ITER safety

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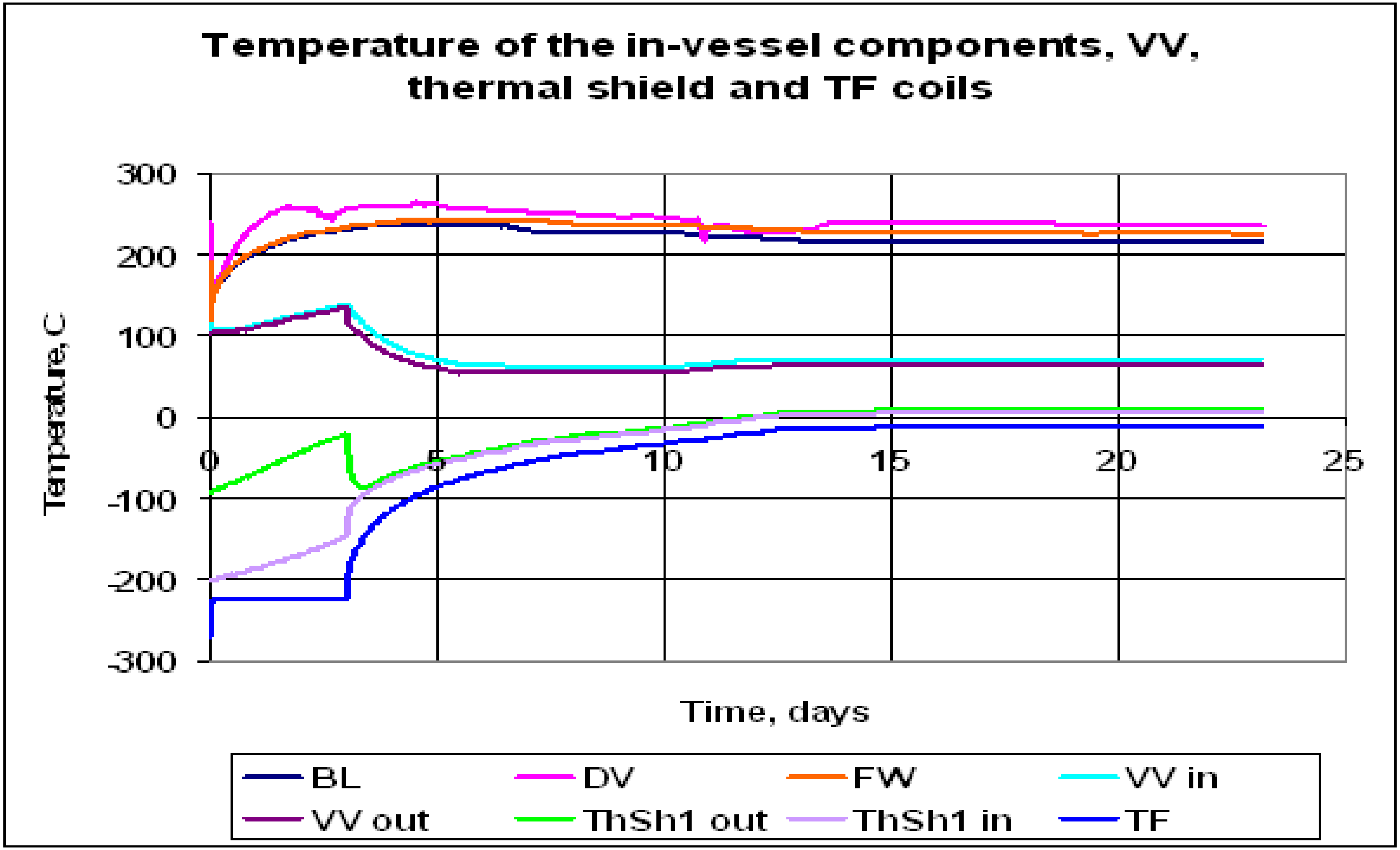
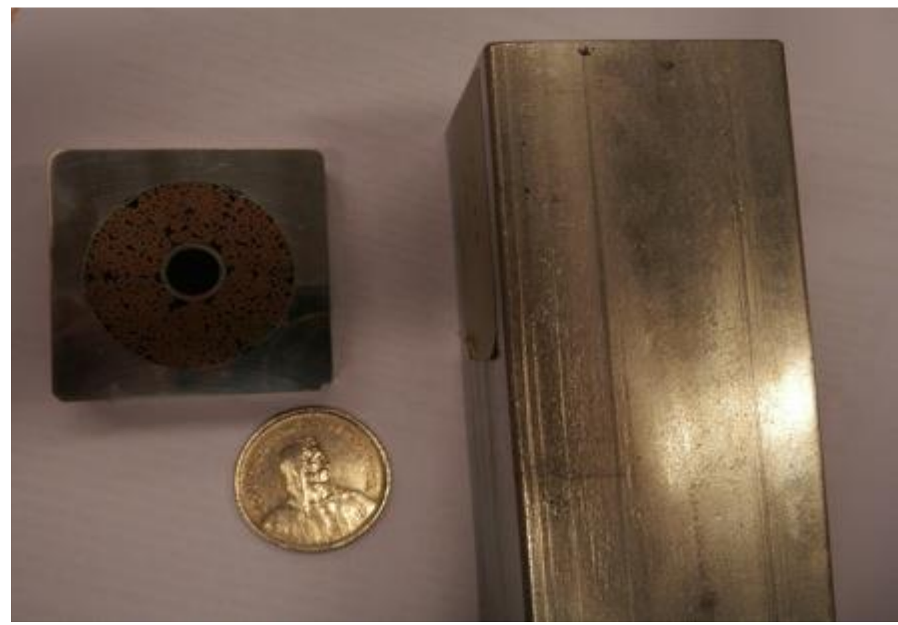


Superconductors

- Coils to create the magnetic configuration of ITER are superconducting (either Nb_3Sn or NbTi)

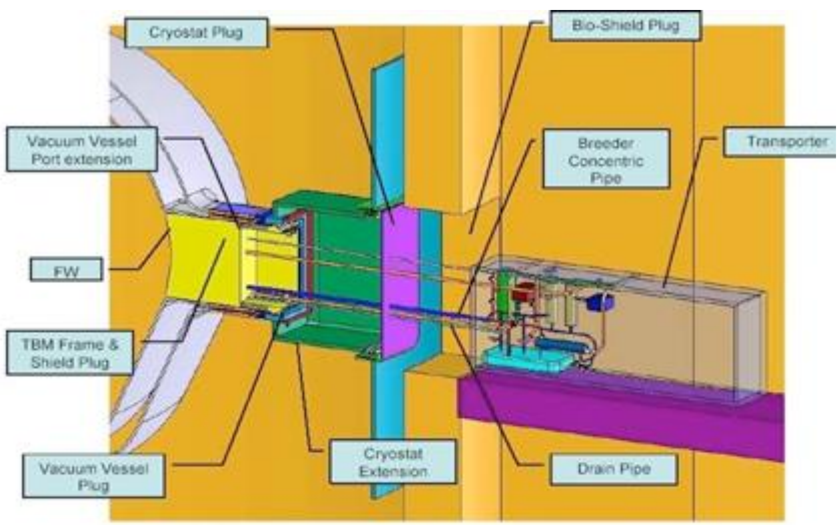
NB_3Sn condcutors for CS (left) and TF (right) coils

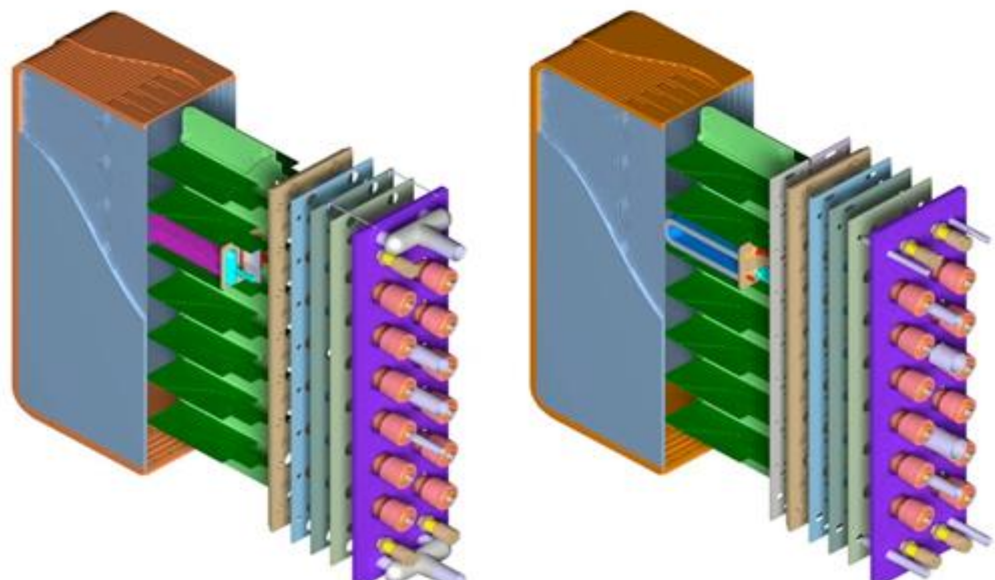


Toroidal field coils (ITER)

Some features of ITER

- ITER will include Test Blanket Modules (TBMs), which are mock-ups of Breeding Blanket for a reactor





EU HCLL and HCPB TBM

TBM

Liquid Breeders Designs	Solid Breeders Designs

Lithium-Lead concepts

- Helium-Cooled design *(EU)*
- Dual-Coolant (He+LiPb) design *(US, India)*
- Dual-Functional design, which is initially a HCLL evolving later to DCLL *(China)*

Molten Lithium concepts

- Self-Cooled design (SCLi) *(RF)*
- He-Cooled design type (HCLi) *(Korea)*

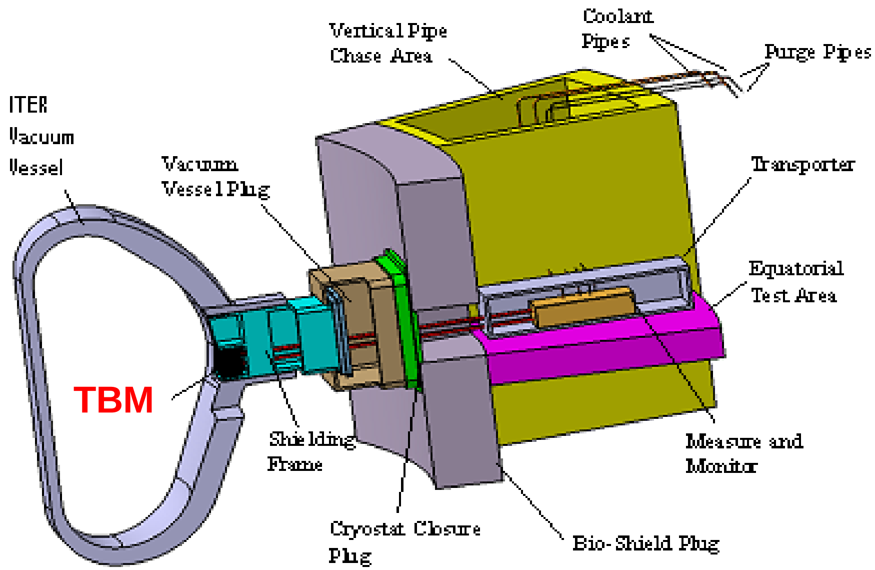
He-Cooled Ceramic Breeder concepts

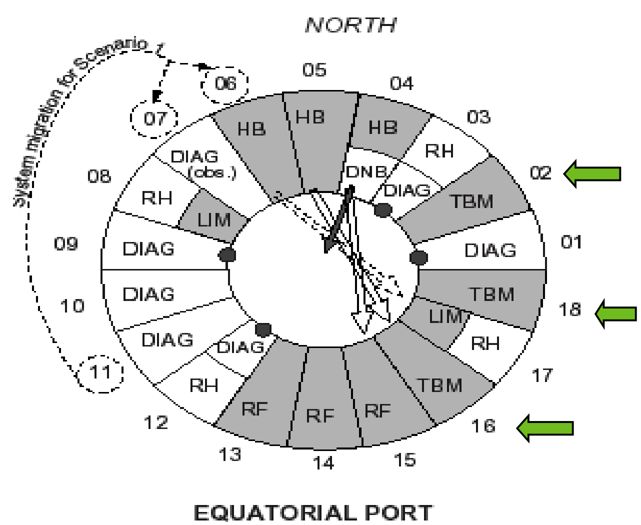
- proposal to install a specific-design TBM *(China, EU, India)*
- proposal to contribute with a specific-design sub-module in other Parties TBM *(Korea, Japan, RF, USA)*

Water-Cooled Ceramic Breeder concept

- specific-design TBM *(Japan)*

TBMs tests need a whole TBM system

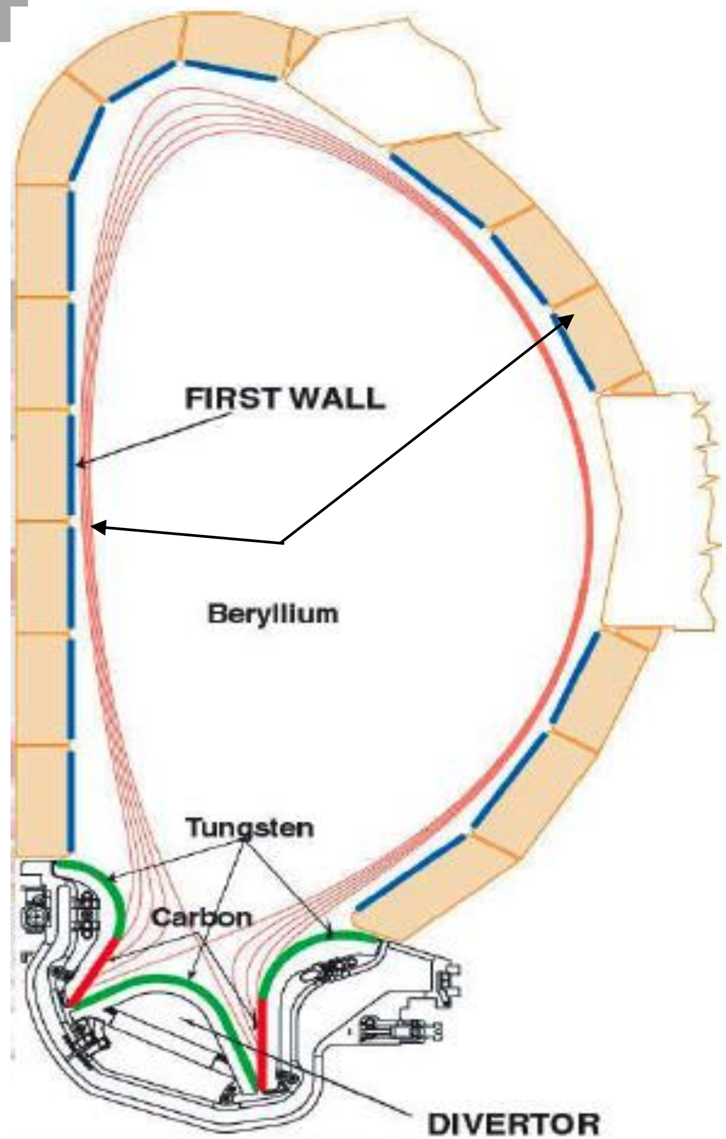




TBM PORTS

Plasma facing components (ITER)

- **CFC divertor targets (~50m²):**
  - high thermal conductivity and good thermal shock resistance (doesn't melt)
  - but combines chemically with hydrogen (ie tritium)
- **Be first wall (~700m²):**
  - good thermal conductivity
  - low-Z_i – low core radiation
  - melting during VDEs
- **W-clad divertor elements (~100m²):**
  - high melting point and sputtering resistance
  - but might still melt during thermal transients
  - will eventually replace CFC



Heating and Current Drive in ITER

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- ITER will have 3 methods to heat and perform non-inductive current:
- Electron cyclotron wave at 170 GHz and 20 MW power deposited to plasma
- Ion cyclotron wave in the frequency range of 55 MW and 20MW at plasma
- Neutral beam injection at 1 MeV and about 30 A

Where are we?

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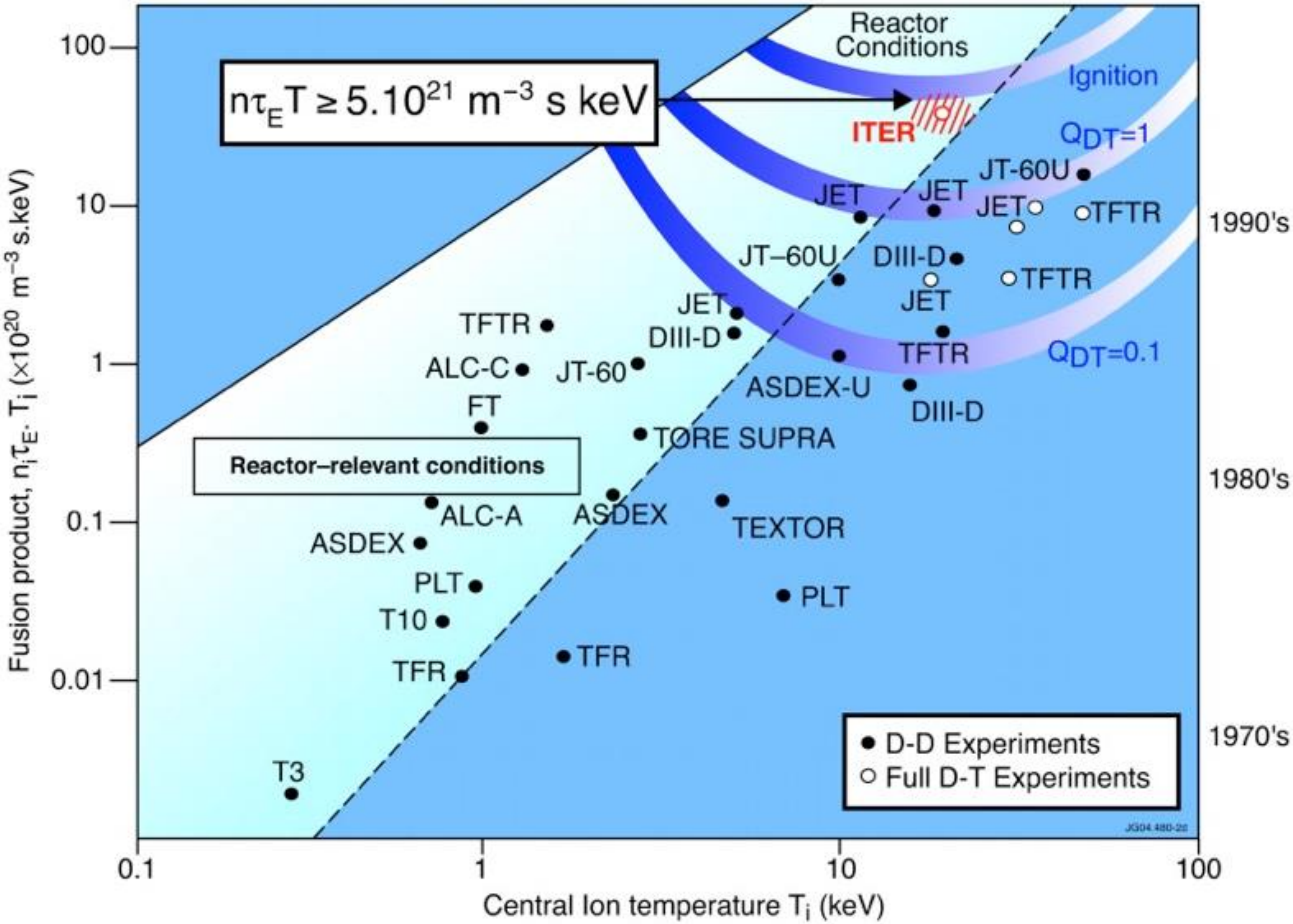
- Ho



Another way to ask the question (courtesy of IO)

- Electrical power consumption to answer the question: Steady state:120 MW continuous power consumption, 180 MVA connected loads (mainly motors), During plasma pulse: 500 MW peak pulse consumption, 2.2 GVA connected power converters

The roadmap towards fusion

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- The roadmap is NOT a single machine but rather a programme:

1. Build and exploit ITER
2. A programme on material based on an Early Neutron Source /IFMIF
3. Preparation of DEMO to be operational by 2050

The Roadmap

JET

Man

From Chinese Road map:
DEMO: 2030
FPP: 2050

ENS/IFMIF

2015

2025-2030

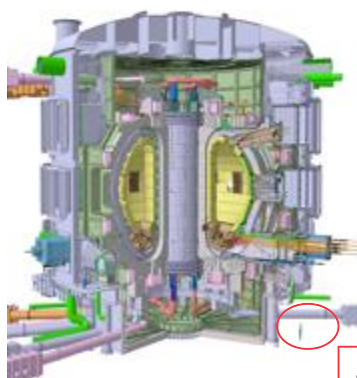
2050

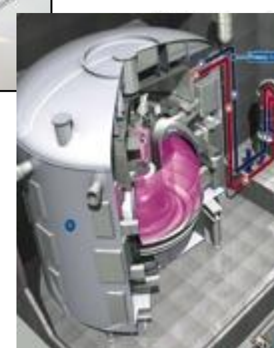
Present experiments + JET 15 MW_{th}

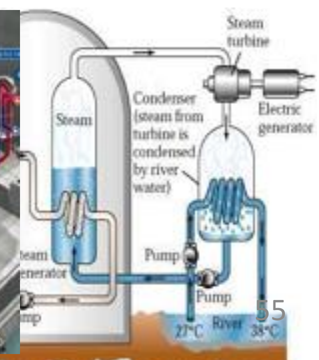
ITER
In construction
500 MW_{th}

DEMO
Preconceptual design
500 MW_{e}

Fusion Power Plant
1.5 GW_{e}







Man

Why do we need a dedicated n source?

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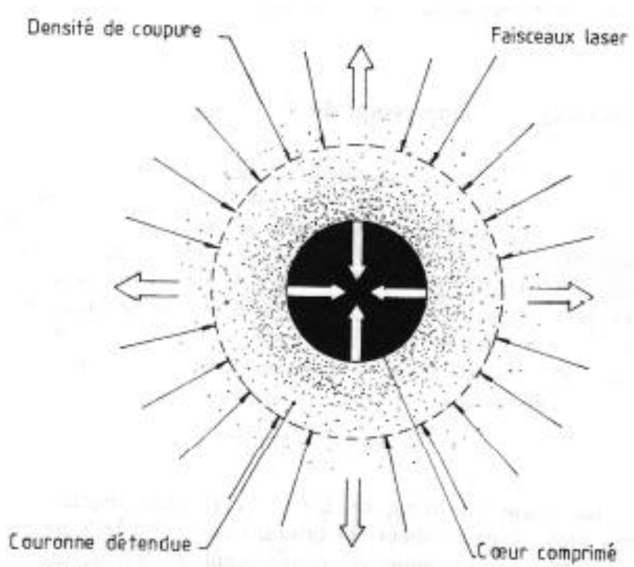
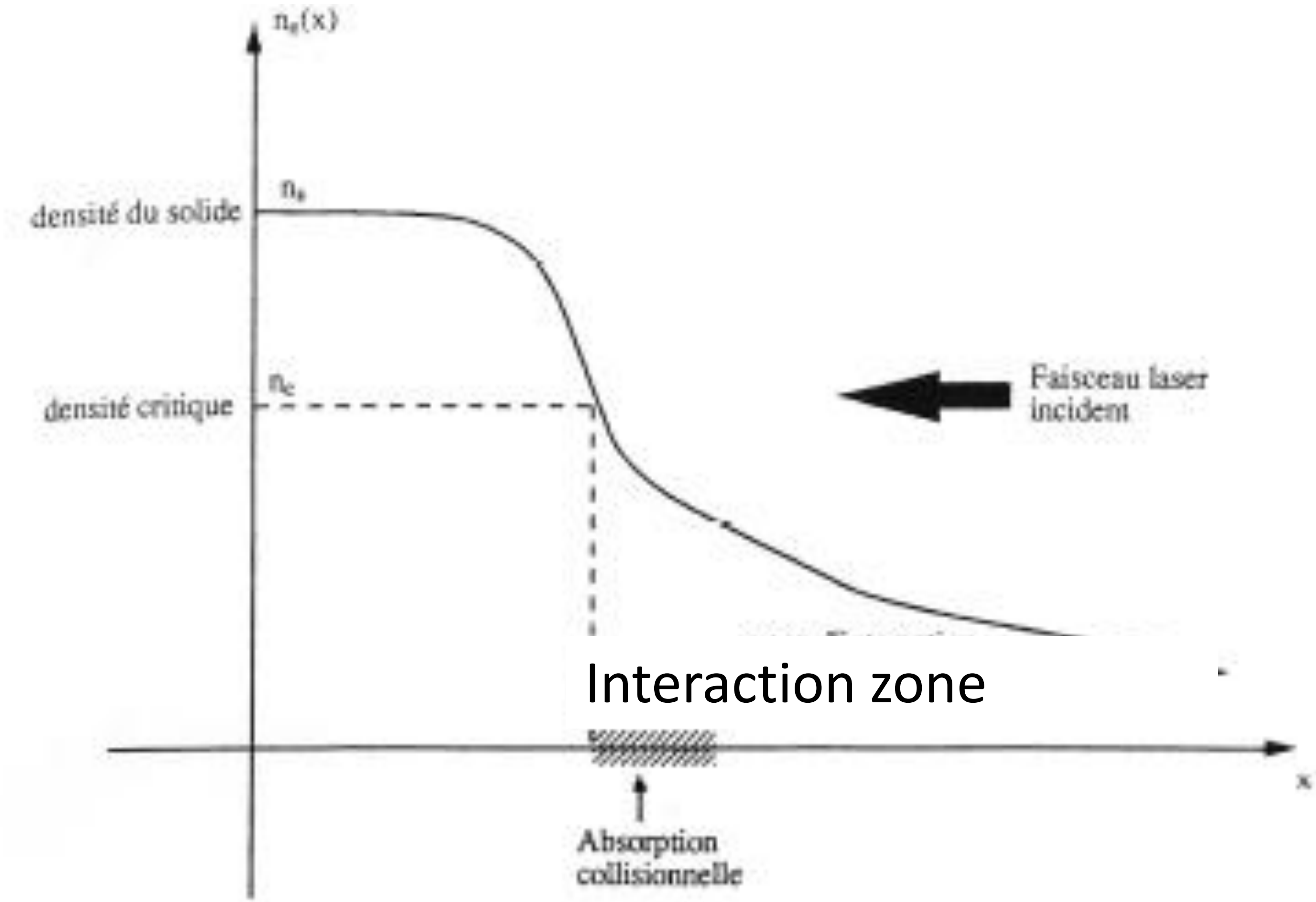
- The fusion reactions produces neutron with a well defined energy of 14 MeV and hence to test material one needs a high flux and fluence source close to this energy (Cf. Dr. J. Knaster talk P9)
- Transmutation; Frenkel pair formation; He and H embrittlement ($^{56}Fe(n,\alpha)^{53}Cr$ (incident n threshold at 2.9 MeV) and $^{56}Fe(n, p)^{56}Mn$ (incident n threshold at 0.9 MeV)
- Interaction of the 14 MeV with material

Inertial fusion

- The plasma is NOT confined. Its expansion rate is given by the ion acoustic speed $c_s = (k_B T/ \text{Ion mass})^{0.5}$

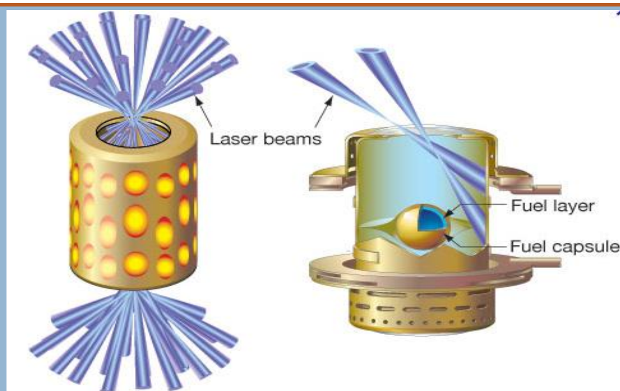


EM wave interaction with plasma

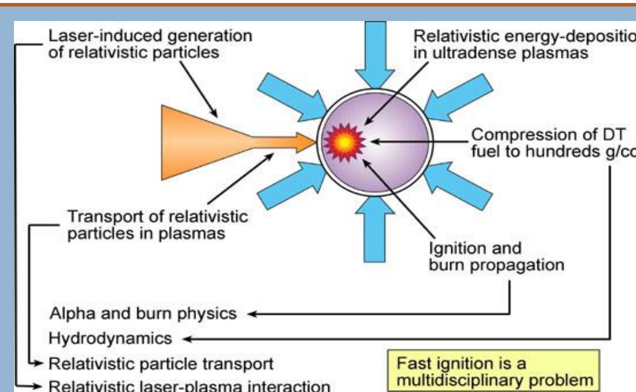


The prospect of inertial fusion energy derives from scientific advancements in different arenas

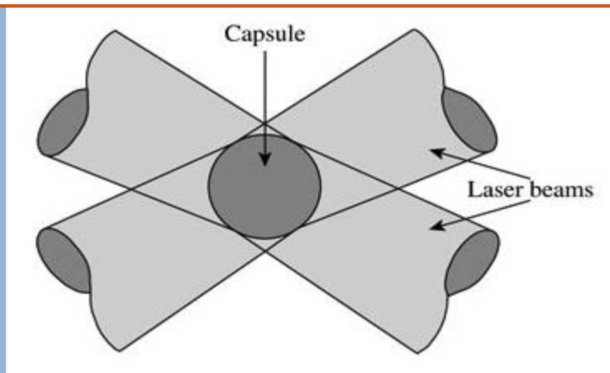
Indirect Drive Laser Fusion: Central Hot Spot Ignition



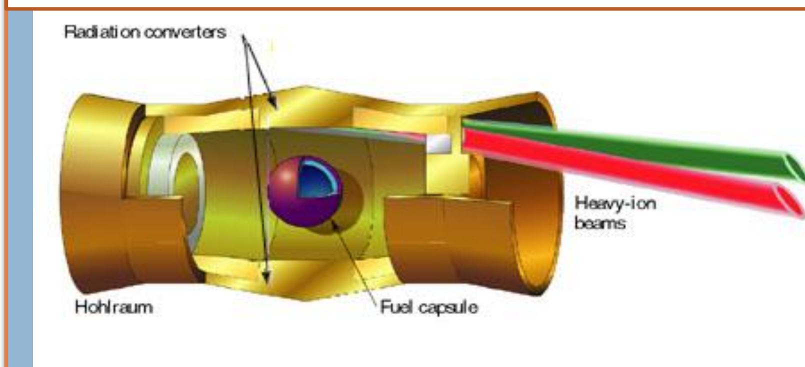
Fast Ignition/Shock Ignition



Direct Drive Laser Fusion: Central Hot Spot Ignition



Heavy Ion Fusion



How ICF could be achieved

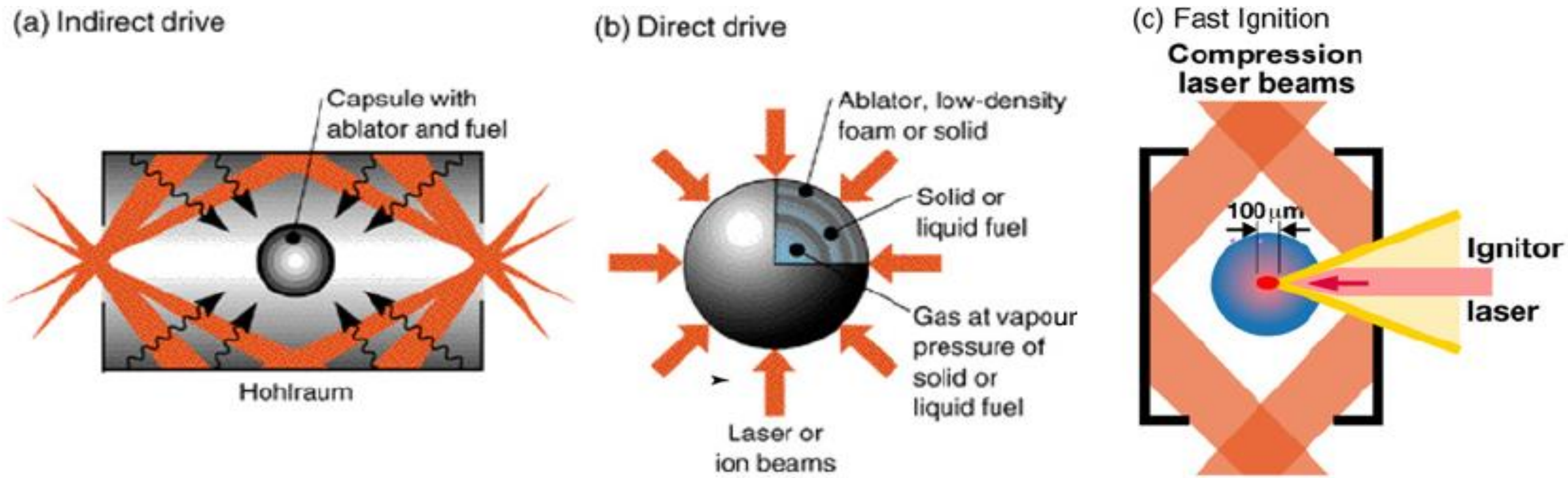


Figure 1. Illustration of ICF target concepts (*a*) indirect drive, (*b*) direct drive and (*c*) fast ignition.

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Ignition on the National Ignition Facility: a path towards inertial fusion energy

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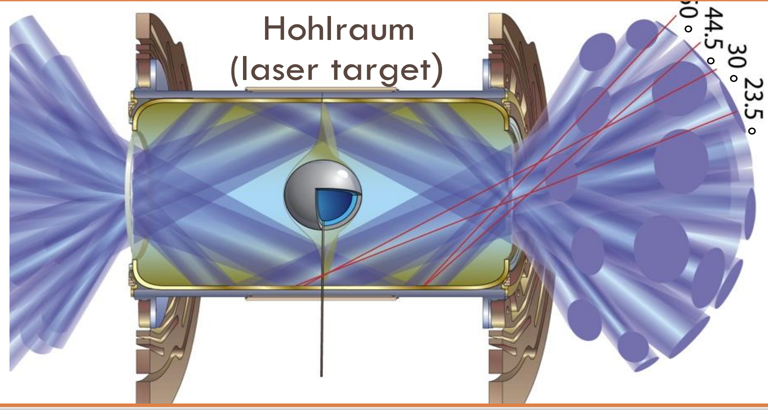
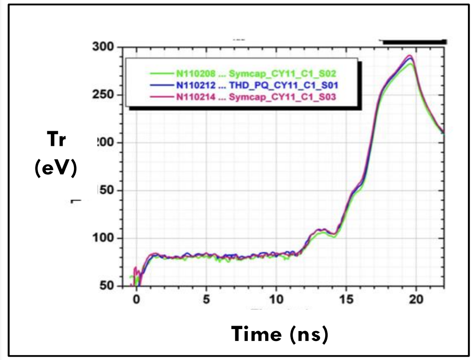
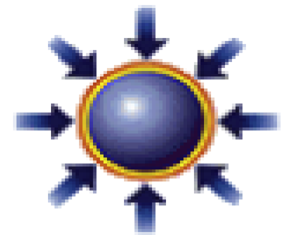
The National Ignition Facility (NIF) provides the opportunity for ignition physics research at full scale

Coupling: laser energy couples to hohlraum and converts to x-rays



Drive: x-rays bathe capsule, heating it up -- it expands





Ablator heats up

Symmetry: radiation compresses capsule and it implodes

Rocket effect

- conservation of momentum: ablated shell expands outward, rest of shell (frozen DT) is forced inward

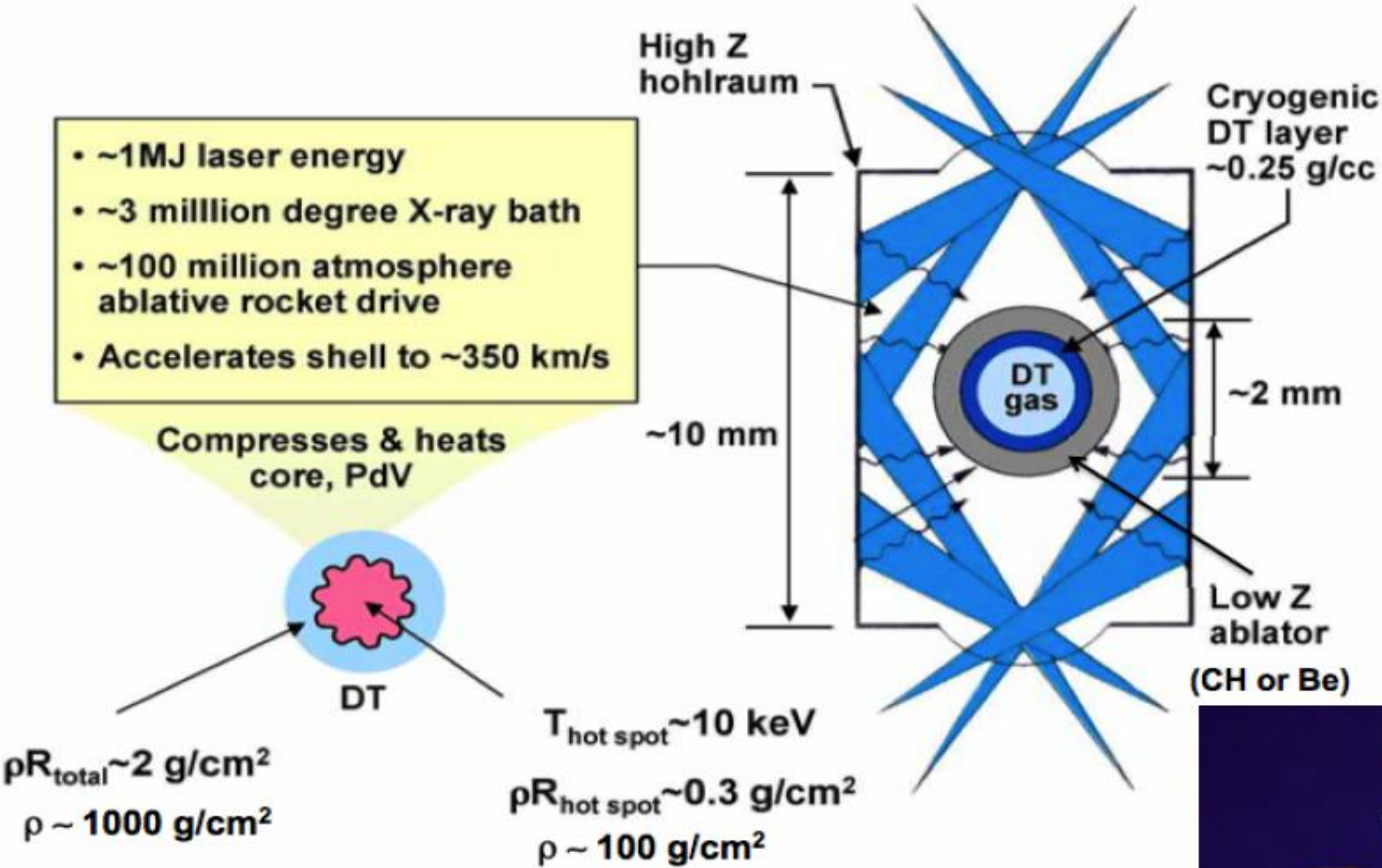
Fusion initiates in a central hot spot and a burn front propagates outward

Ignition

Burn wave

On NIF we use a hohlraum driven implosion to generate the ρR & T needed for ignition

OV/2-1 Lindl

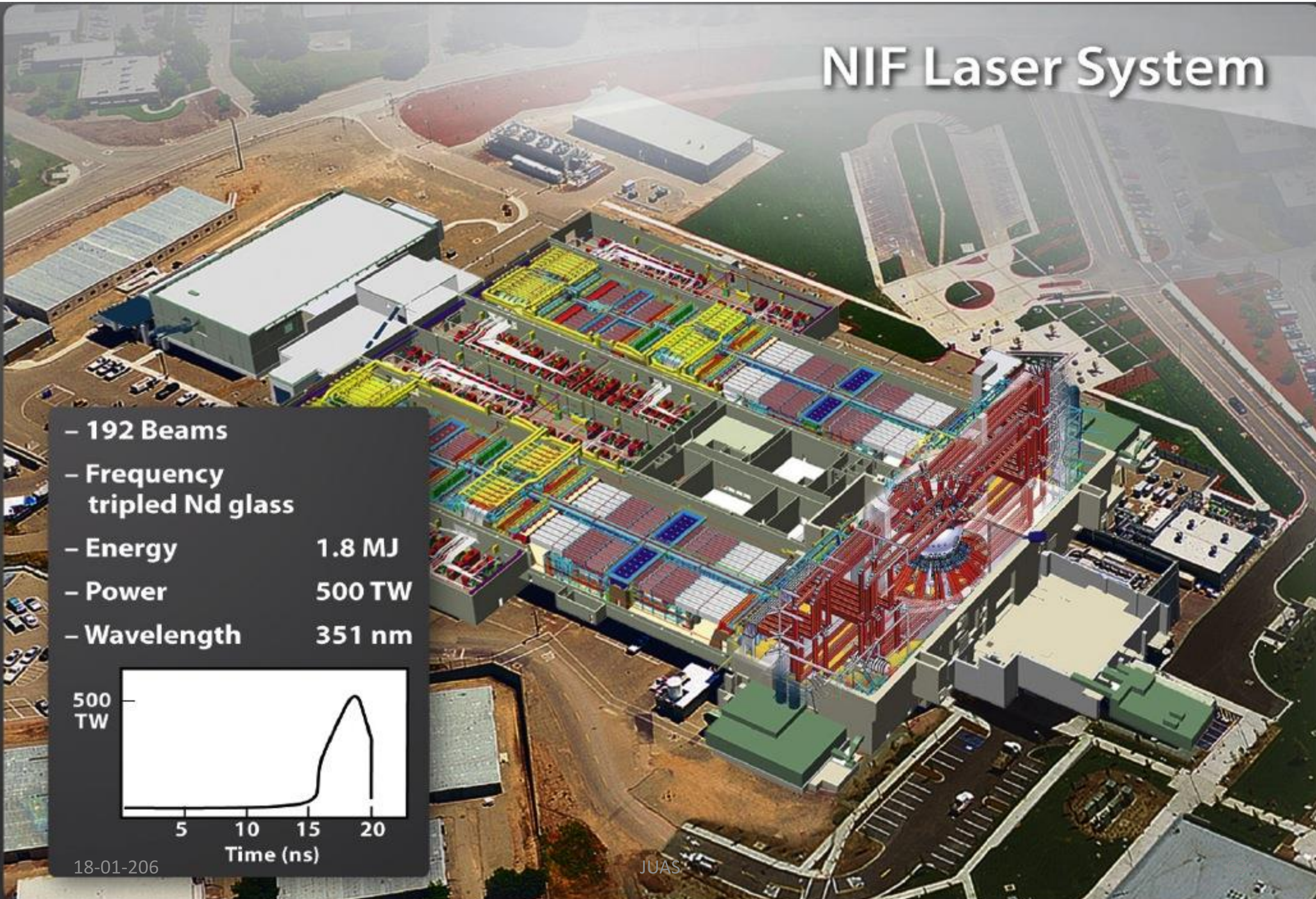


NIF Laser System

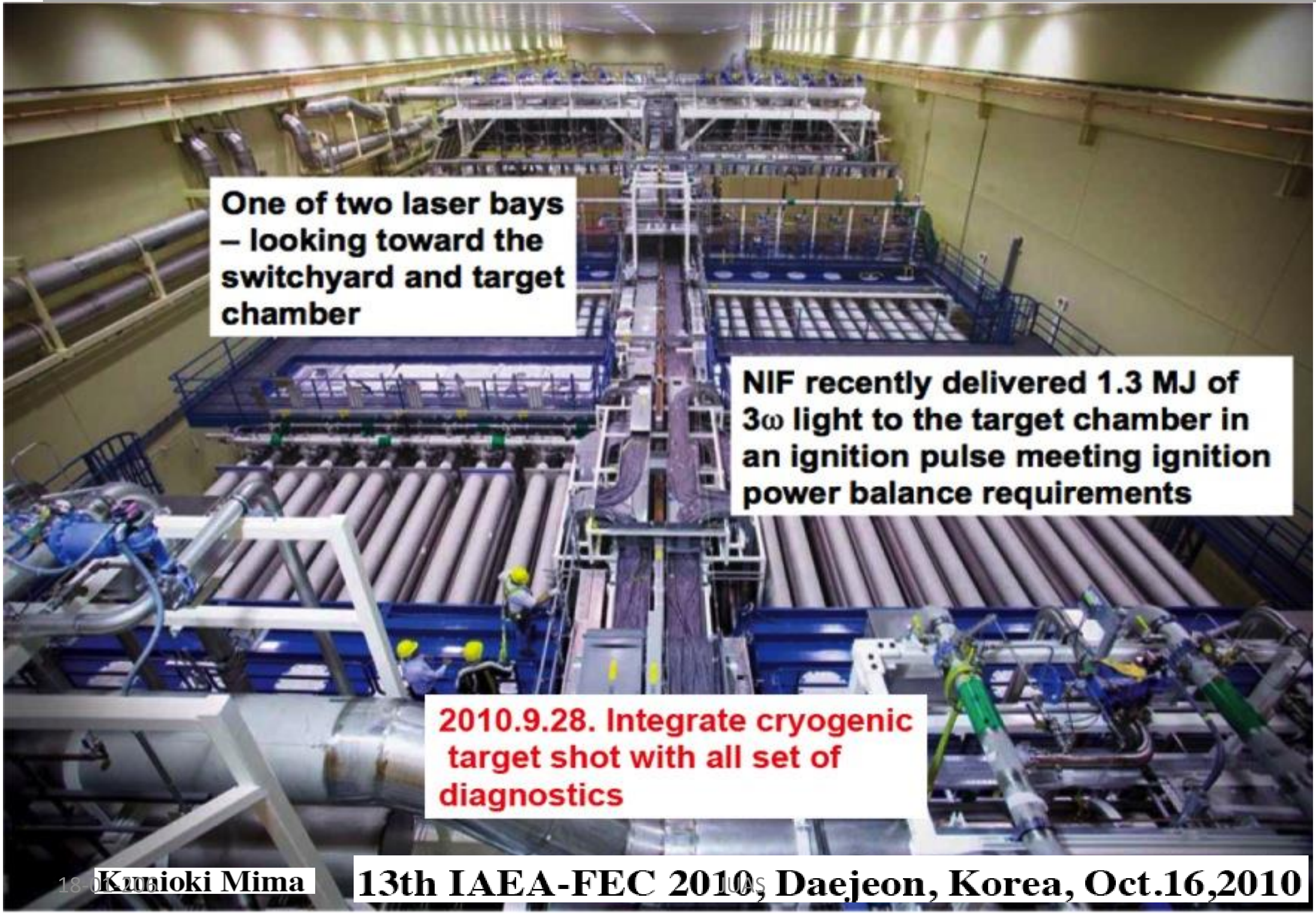
– 192 Beams

– Frequency tripled Nd glass

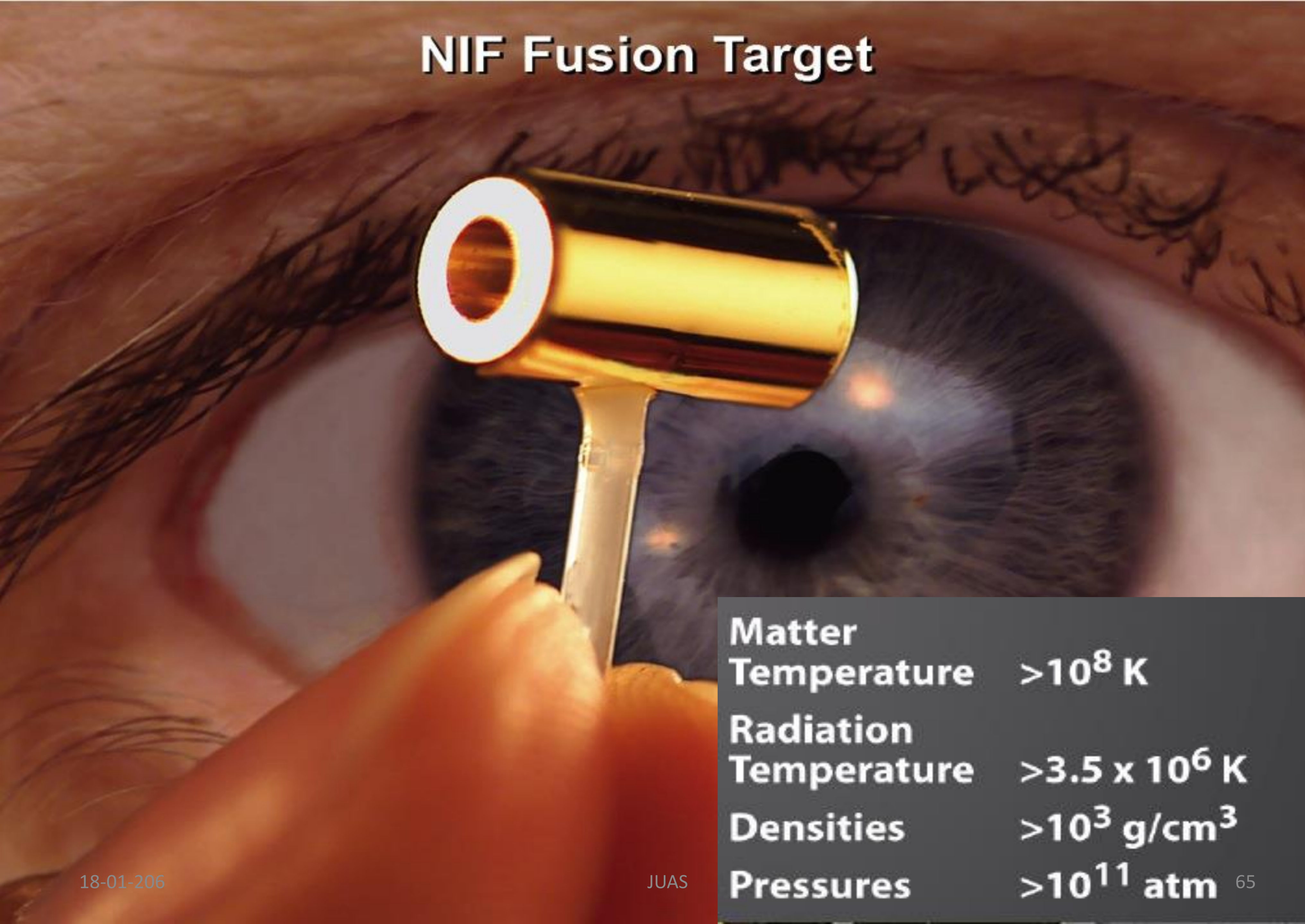
– Energy	1.8 MJ
– Power	500 TW
– Wavelength	351 nm



NIF laser amplifiers



NIF Fusion Target



Matter Temperature	$>10^8$ K
Radiation Temperature	$>3.5 \times 10^6$ K
Densities	$>10^3$ g/cm^3
Pressures	$>10^{11}$ atm

The hohlraum

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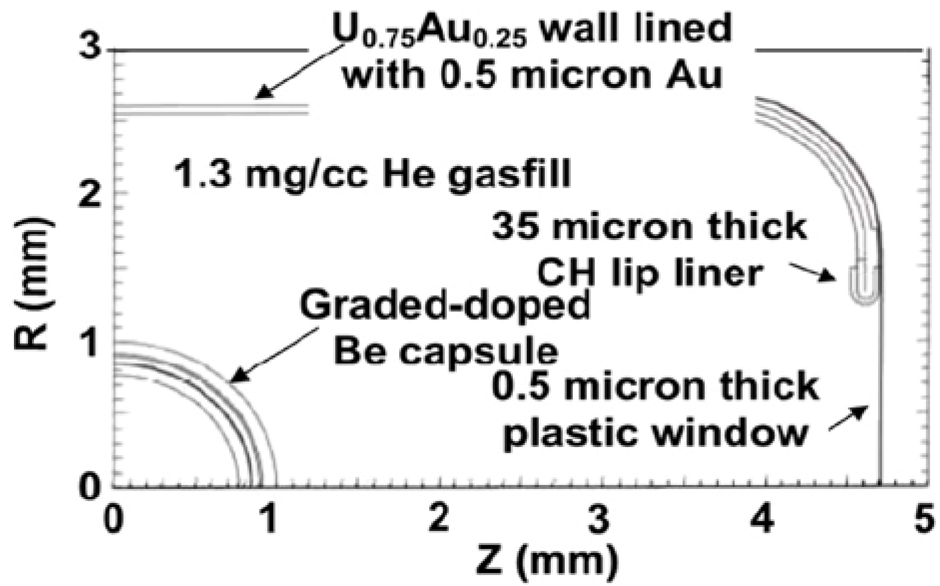

Figure 2. Diagram of 1/4 of the 300 eV hohlraum. Capsule radius is 1 mm, hohlraum half length is 4.6 mm and hohlraum radius is 2.55 mm. Inner cone beams enter at angles of 23.5° and 30° from axis with laser spots of $590 \times 824\ \mu m^2$ (semi minor and major axes of ellipse). Outer cone beams come in at 44.5° and 50° with spots of $343 \times 593\ \mu m^2$ (semi minor and major axes of ellipse).

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Summary of inertial fusion sessions

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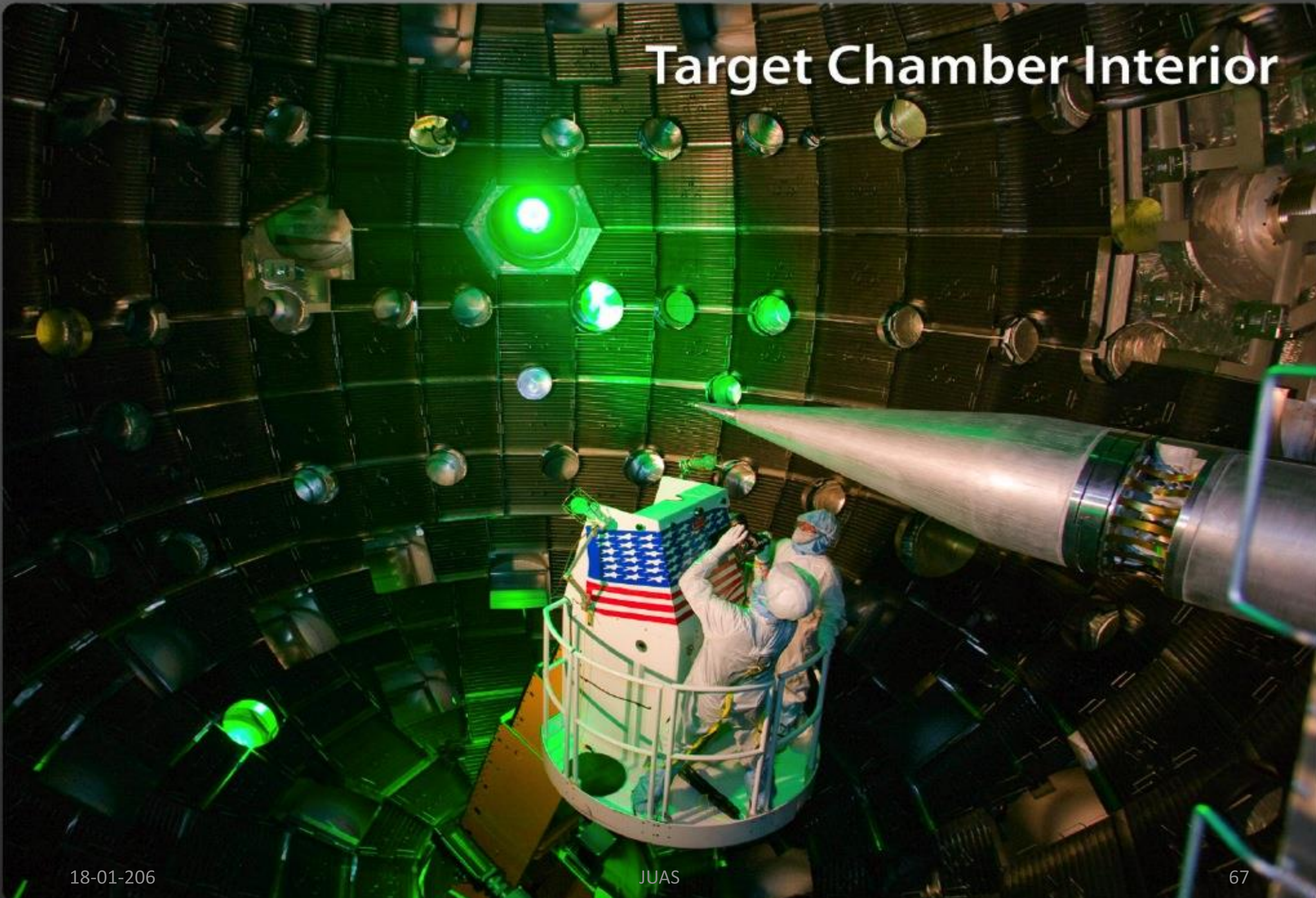
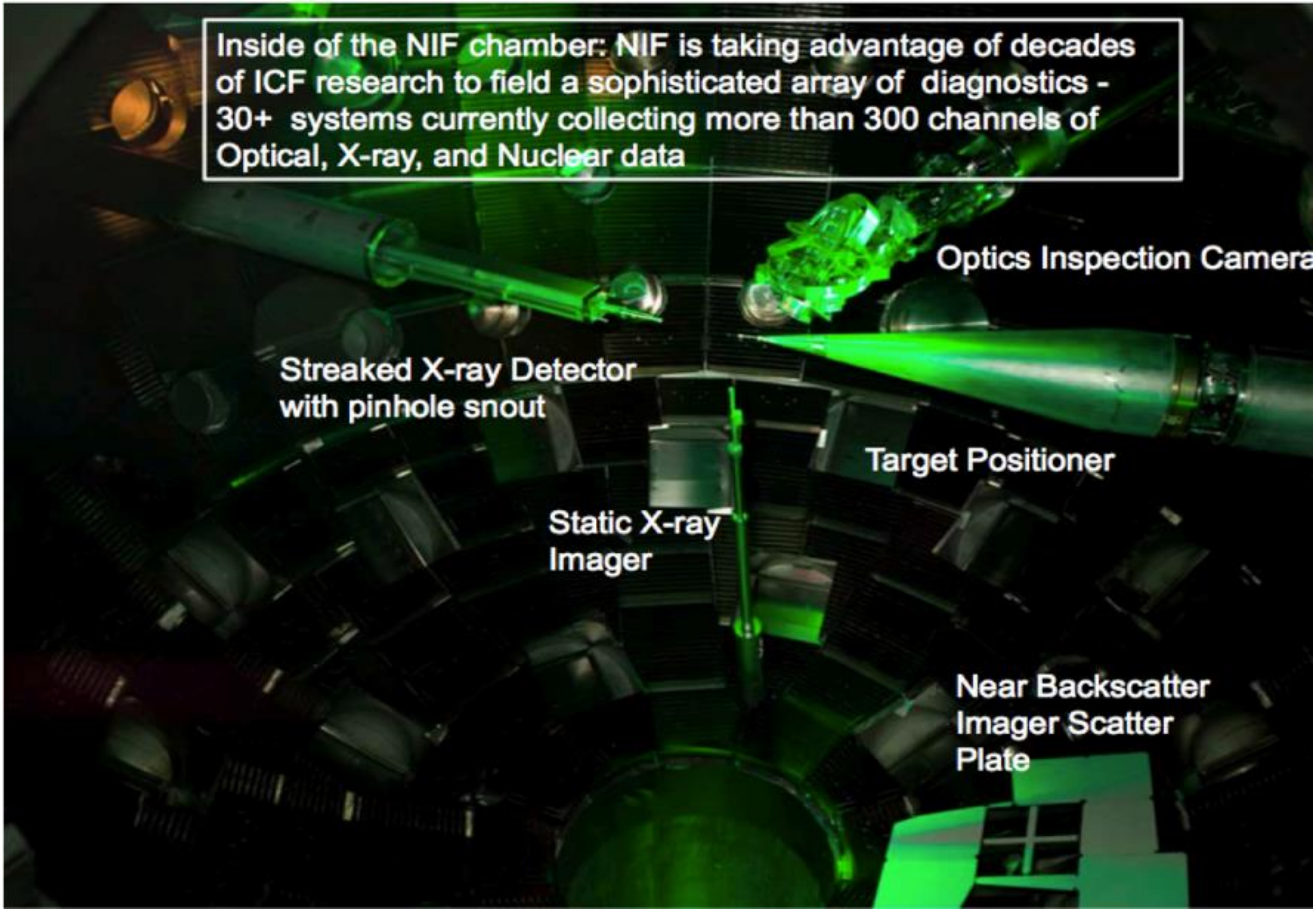
Target Chamber Interior




Inside of the NIF chamber: NIF is taking advantage of decades of ICF research to field a sophisticated array of diagnostics - 30+ systems currently collecting more than 300 channels of Optical, X-ray, and Nuclear data
Optics Inspection Camera
Streaked X-ray Detector with pinhole snout
Target Positioner
Static X-ray Imager
Near Backscatter Imager Scatter Plate

Conclusion

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22nd World Energy Congress, Daegu 2013

Capturing the Moments

20 November 2013

"The fusion challenge is much bigger than Apollo … It's like a mission to Mars or jumping from the Wright brothers airplane to the jet engine." It is generally agreed that the middle of this century is a realistic timeline for commercial scale fusion energy, though some it can happen faster.

- ***Nebojsa Nakicenovic***, *Deputy Director & Deputy CEO of IIASA*

Thank you for your attention