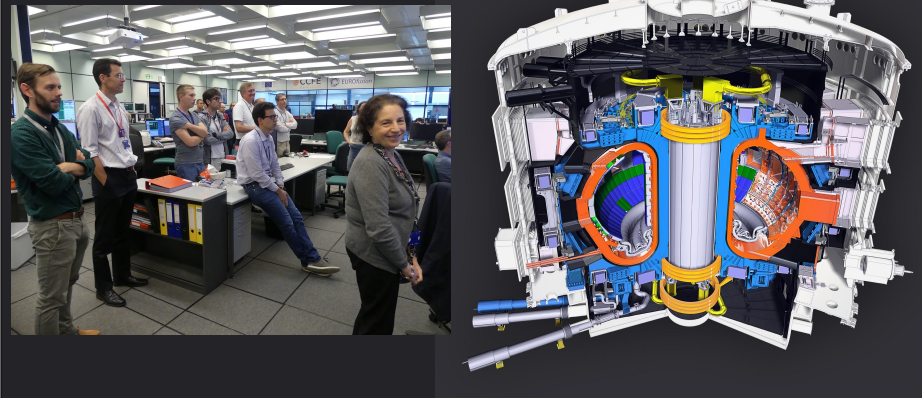


Nuclear fusion, an important option for our energy future slide 1



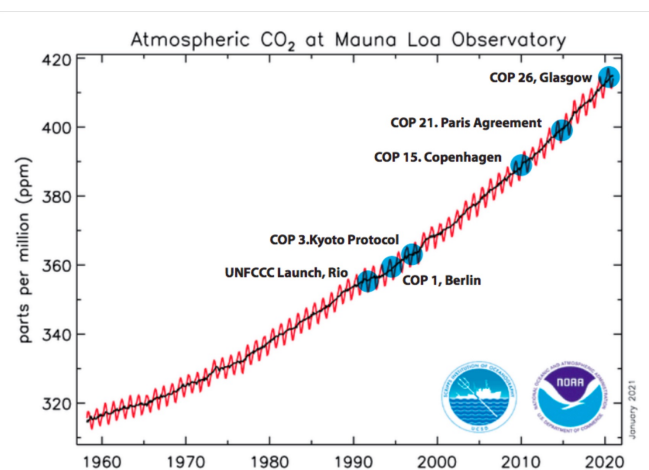
Jef Ongena

Plasma Physics Lab, Royal Military Academy, Brussels
 Member of the Royal Flemish Academy of Belgium
 SEII, Chateau St-Anne
 24 April 2026

Introduction

30 years worldwide investments (> 15 000 billion Euro...) without clear results

Enormous blackouts with wind and solar ... We need backbone power !



slide 3

Justified question :

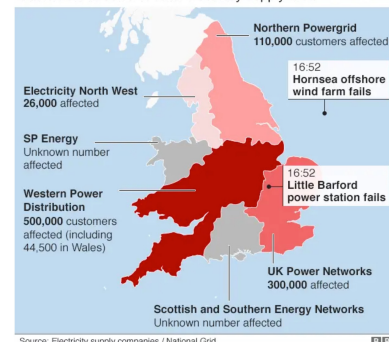
Are we doing what is needed ? Revision of plans with wind and solar ?

Additional clean sources : fission and fusion !

UK, 9 August 2019, **wind farm failed** Spain and Portugal, 28 April 2025 slide 4

England and Wales power cut

Customers affected in each electricity supply area



Source: Electricity supply companies / National Grid



Spain declares state of emergency as power blackout chaos continues | BBC News

London without power...

Spain and Portugal without power...

Other countries (or big parts of Europe) ... next blackout ...?

1. Renewable energy: wind, solar, hydro...
2. Fossil energy sources: oil, coal, gas (>80% of total and INCREASING!)
3. Nuclear fission

We need a bigger energy "PORTFOLIO"

Nuclear fusion !
(and it will be NEVER too late...)

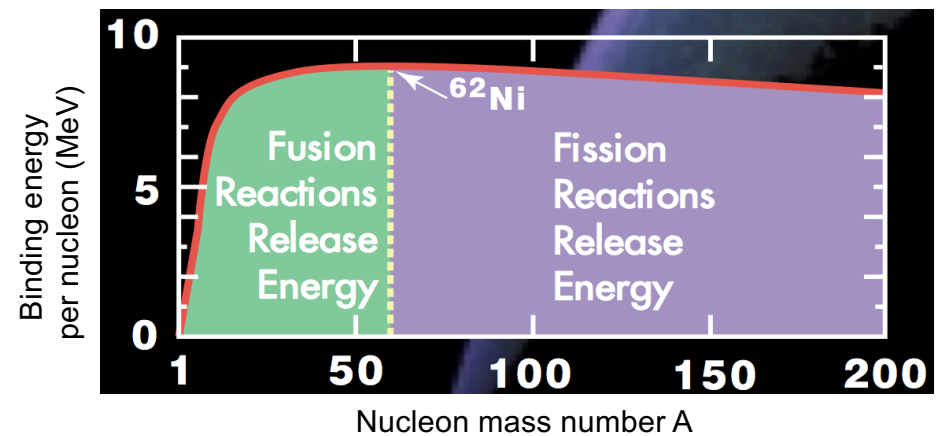
Fusion Principles

Aren't we easing our conscience with wrong arguments ?

1. Not wise to base our energy economy on only 1 'pillar' to produce energy
1. The variability of renewable energy necessitates storage / backup
2. Storage is not simple, and far from sufficient with current technologies
 - E.g Germany 40 GWh in hydro, compared to a storage need of ~ 10 TWh
 - E.g. largest battery currently is ~ 300 MWh...
3. Integrated energy production values for renewables → distorted message
 - Overemphasizes the real contribution in the absence of storage
 - No inertia : easy blackouts : UK / Spain
4. If renewables cannot meet the demand and nuclear is eliminated
 - Only fossil production remains (remember only 3 methods...)
 - But gas ?? Geopolitical dependency.... ?
 - CO₂ !!!

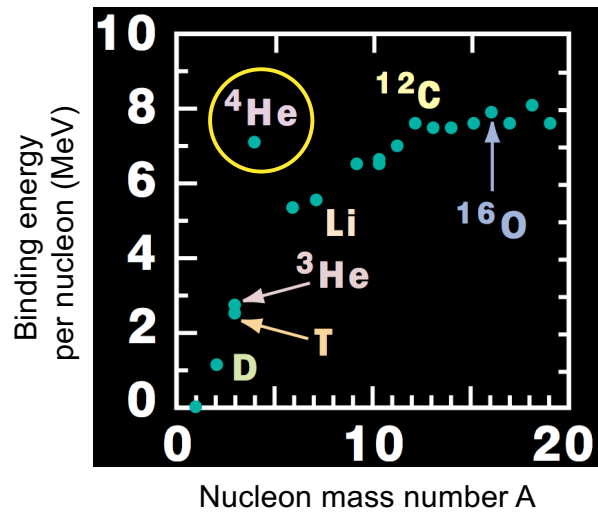
No doom: a bright future for all of you, but work will be needed !

Results from the difference in binding energy
between light nuclei and fusion products



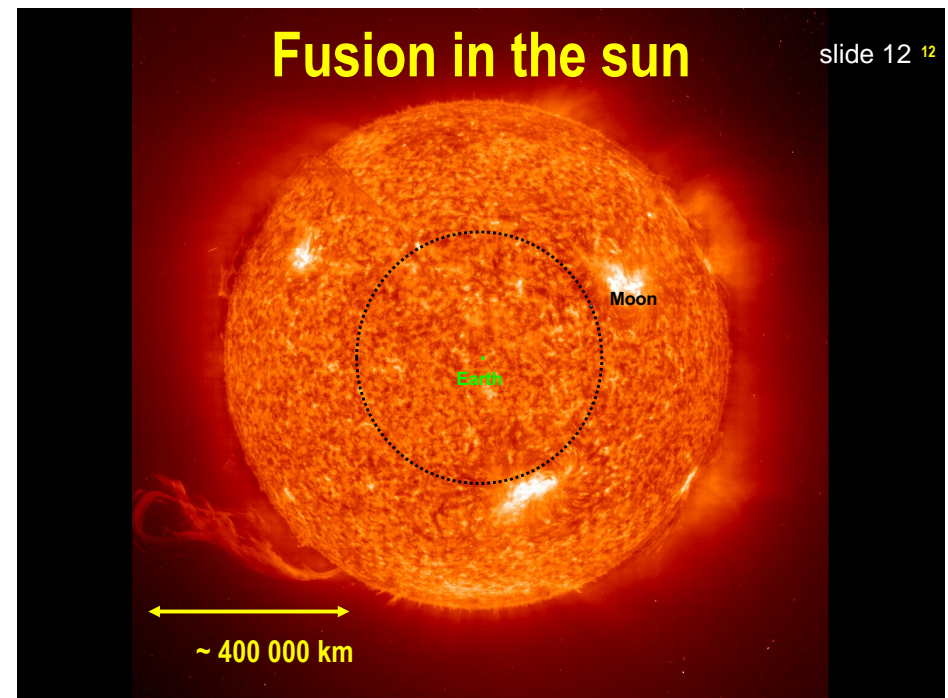
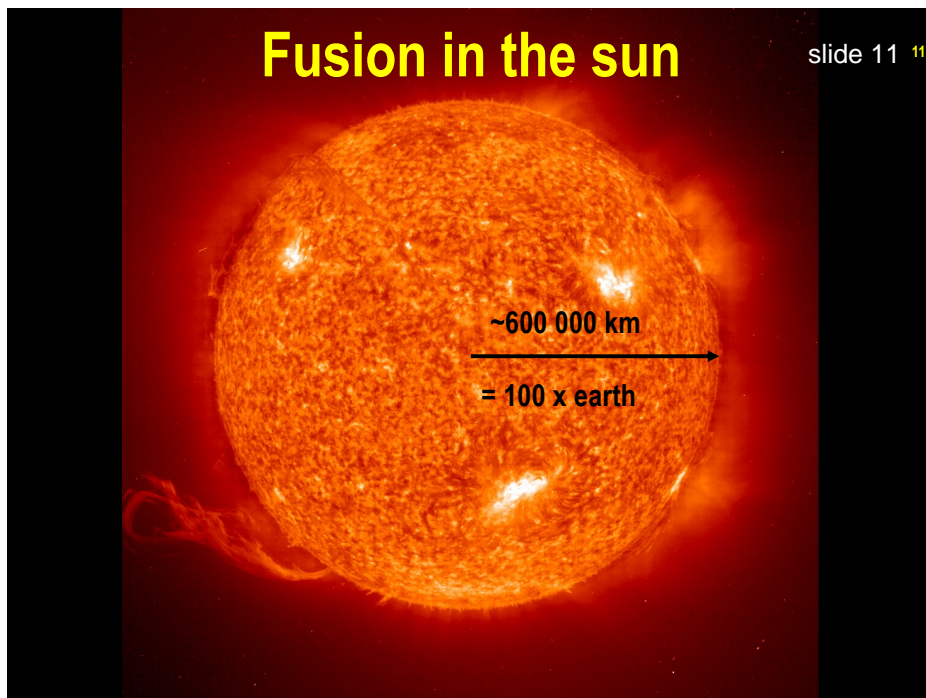
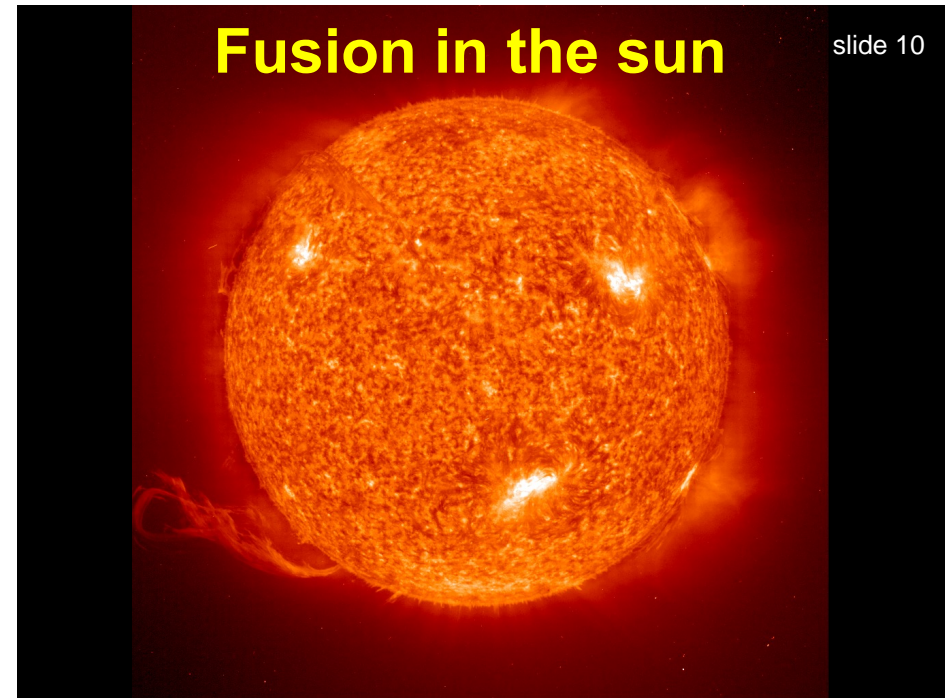
Maximum at ~ ⁶²Ni : tremendous consequences for heavy stars

^4He has a particularly large binding energy



Nucleus	Total Binding Energy (MeV)
D = ^2H	2.22457
T = ^3H	8.48182
^3He	7.71806
^4He	28.29567

Large gain in energy when ^4He is one of the reaction products



Temperature at edge

From Stefan-Boltzmann law and measured Luminosity L

$$L = 4\pi\sigma R_{\text{sun}}^2 T_{\text{edge}}^4 \rightarrow T_{\text{edge}} = 5780\text{K}$$

(σ = Stefan-Boltzmann constant = $5.670 \times 10^{-8} \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1}$)

Temperature in centre:

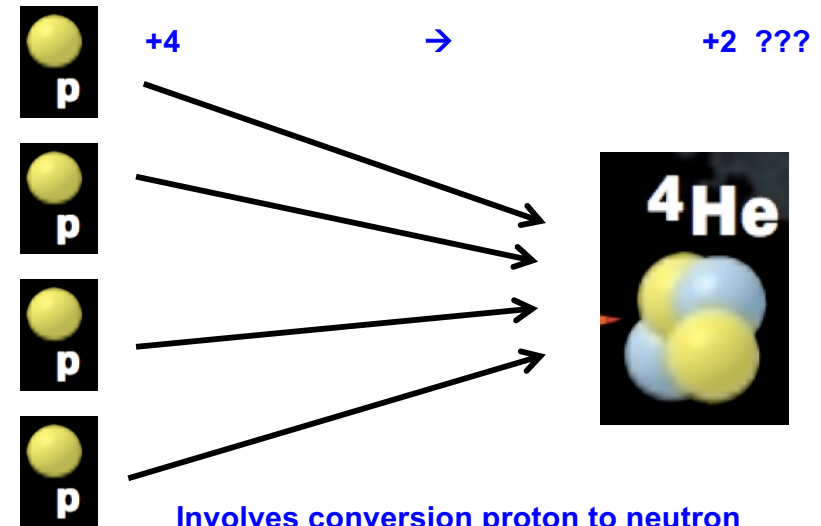
Proton thermal energy in centre (= 3/2 kT) equal to potential energy from gravity per proton:

$$1.5k T_{\text{centre}} = Gm_p M_{\text{sun}}/R_{\text{sun}} \rightarrow T_{\text{centre}} = 15\,600\,000\text{ K}$$

(G=gravitational constant= $6.6726 \times 10^{-11} \text{ Nm}^2\text{kg}^{-2}$
 k=Boltzmann's constant= $1.38 \times 10^{-23} \text{ J K}^{-1}$
 m_p = mass of proton = $1.6726 \times 10^{-27} \text{ kg}$.)



Group #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period 1	1 H	Fusion →																2 He
Period 2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
Period 3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
Period 4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
Period 5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
Period 6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
Period 7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	(117) (Uus)	118 Uuo
* Lanthanoids	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu			
** Actinoids	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr			



Involves conversion proton to neutron
 Very difficult and slow reaction (which is good for us...)
 Sun : Every second : 4 million tonnes transformed → Energy

Fusion on earth

slide 17

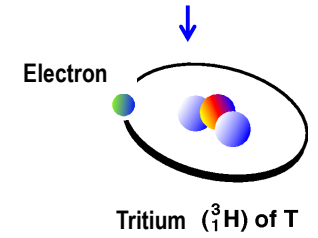
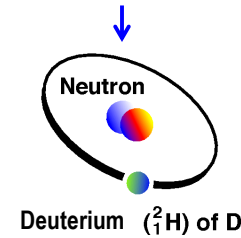
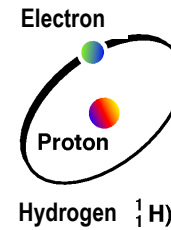


Hydrogen and its isotopes

slide 18 ¹⁸

Sun

On Earth



Natural
isotope
Stable

Natural
isotope
Stable

Artificial
Isotope
Half-life 12.3 years

'Easiest' fusion reactions

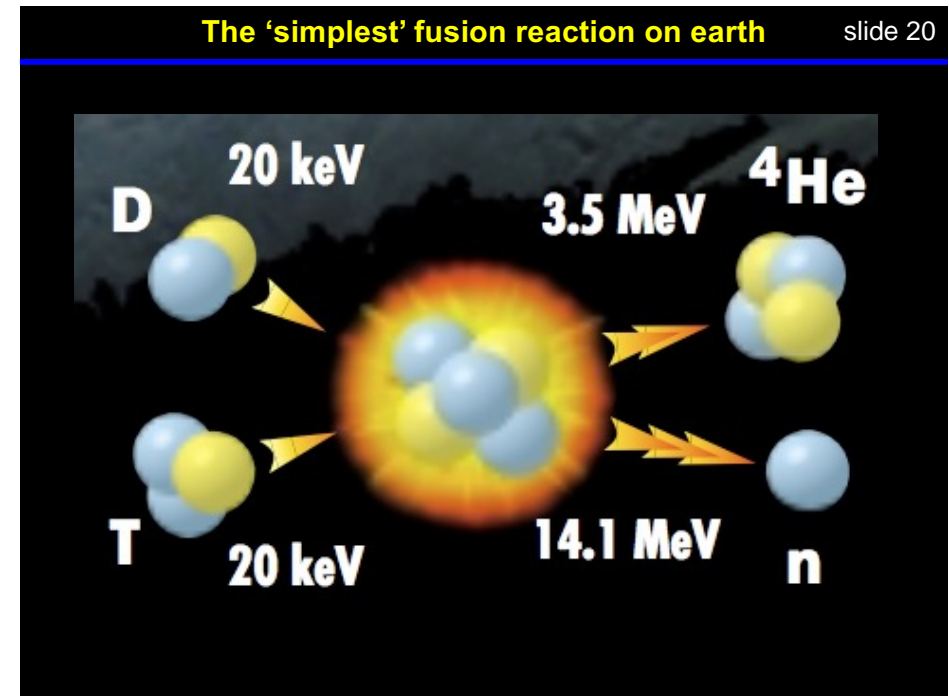
slide 19

Fusion Reaction	Temperature Needed (in Million Degrees)	Reaction Energy (in keV)
$\text{D} + \text{T} \rightarrow \text{}^4\text{He} + \text{n}$	100-200	17,600
$\text{D} + \text{}^3\text{He} \rightarrow \text{}^4\text{He} + \text{p}$	~700	18,300
$\text{D} + \text{D} \rightarrow \begin{cases} \text{}^3\text{He} + \text{n} \\ \text{T} + \text{p} \end{cases}$	~400	~4,000
	~400	~4,000

Extensive database on fusion reactions : http://pntpm3.ulb.ac.be/Nacre/barre_database.htm

The 'simplest' fusion reaction on earth

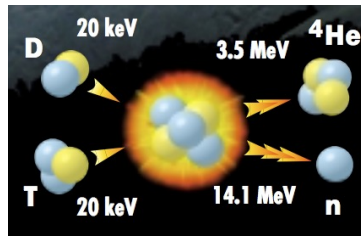
slide 20



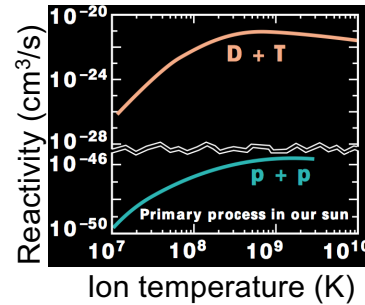
Comparison: fusion reaction on earth and in the sun

On earth (D-T)

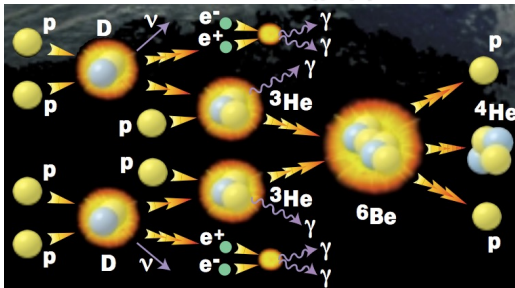
slide 21



D-T reaction has **10^{25} times larger reactivity (cm^3/s)** than the p-p reaction

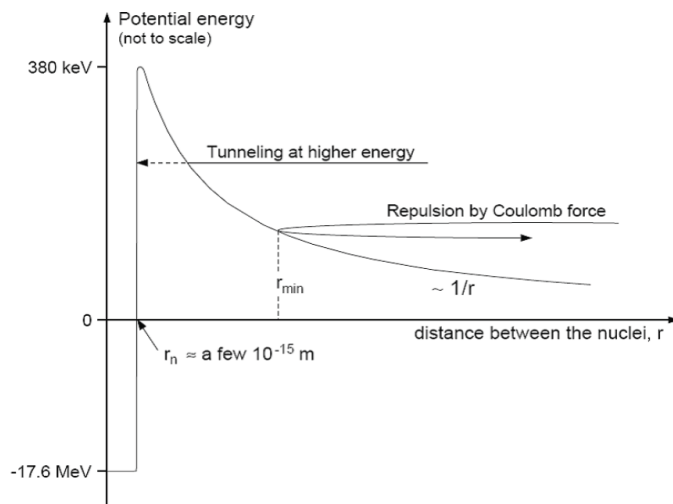


In the sun (p-p)



Most fusion reactions occur through tunneling

slide 23



Advantages of fusion energy

slide 22

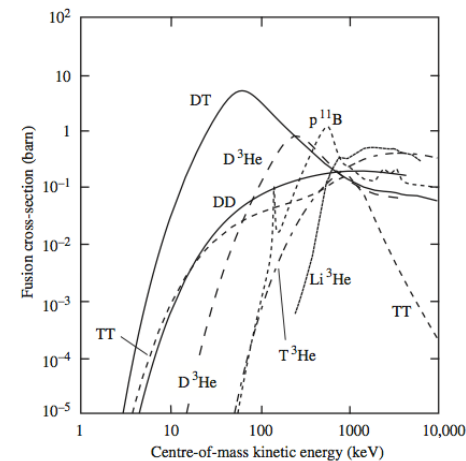
- Minimal environmental
 - Ash = helium = noble gas
 - No greenhouse effect, no ozone layer depletion, no acid rain,....
 - Only gas that remains liquid at 0K = -273.15 K
- No long-term storage required of active waste
 - Tritium consumed in the reaction
 - Recycling of the metals will the reactor after ~100 years
 - Generations that produce waste can recycle it
- Inherently safe
 - No 'runaway' reactions possible, after-heat not in volume
 - No accidents like Tchernobyl / Three Mile Island / Fukushima
- Fuels (Water and Lithium) abundantly available on earth
 - Greatly reduced dependence on supplier (Russia, ...)
 - Minimum consumption: 15g of fuel for 80 years of electricity

BUT difficult: 150-200 million degree needed to start fusion reactions.

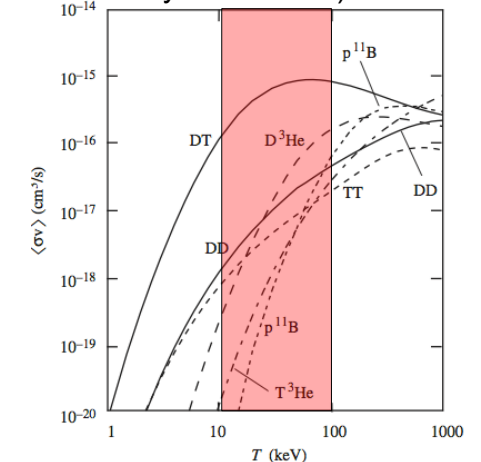
Fusion Cross-Sections and Reactivities

slide 24

Fusion cross-section (in barn = 10^{-28}m^2)



Fusion Reactivity in cm^3s^{-1} (averaged over Maxwellian velocity distribution)



D-T reaction : Maximum for T ~ 10-15 keV

Fusion power:

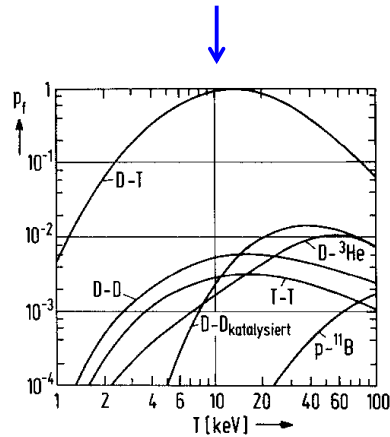
$$P_{\text{fusion}} \sim n^2 \langle \sigma v \rangle E_{\text{fus}}$$

At fixed pressure

$$p = \text{cte} = nkT \rightarrow n \propto 1/T$$

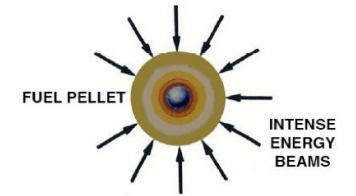
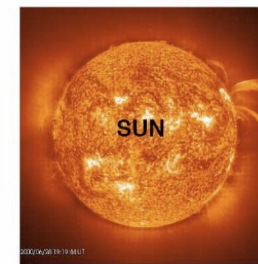
Thus :

$$P_{\text{fusion}} \sim \langle \sigma v \rangle E_{\text{fus}} / T^2$$

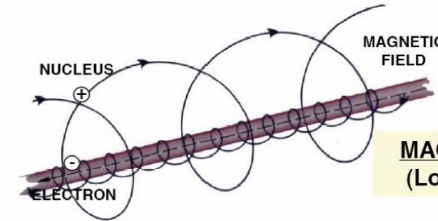


P_{fusion} normalized to max of D-T

GRAVITATIONAL CONFINEMENT
(High density for billions of years)



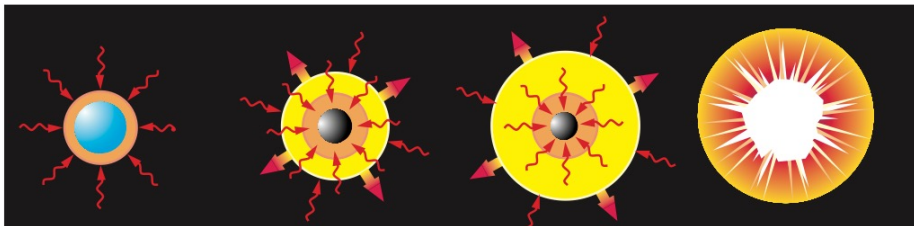
INERTIAL CONFINEMENT
(High density for less than a billionth of a second)



MAGNETIC CONFINEMENT
(Low density for seconds)

Realizing Fusion
A. Inertial Fusion

Using powerful laser or particle beams to compress a tiny pellet



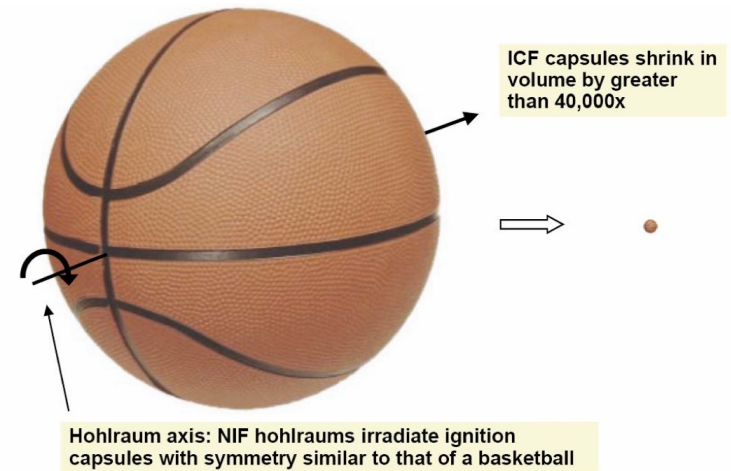
Surface Heating

Compression

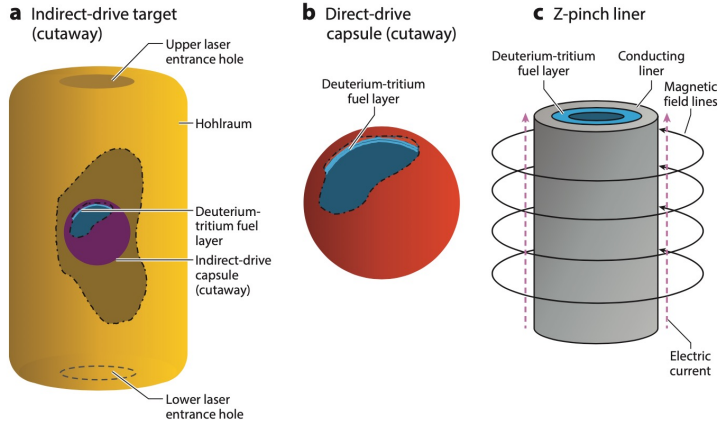
Ignition

Fusion

Realizing Fusion
A. Inertial Fusion



Very powerful laser systems needed
High requirements for isotropic illumination of target

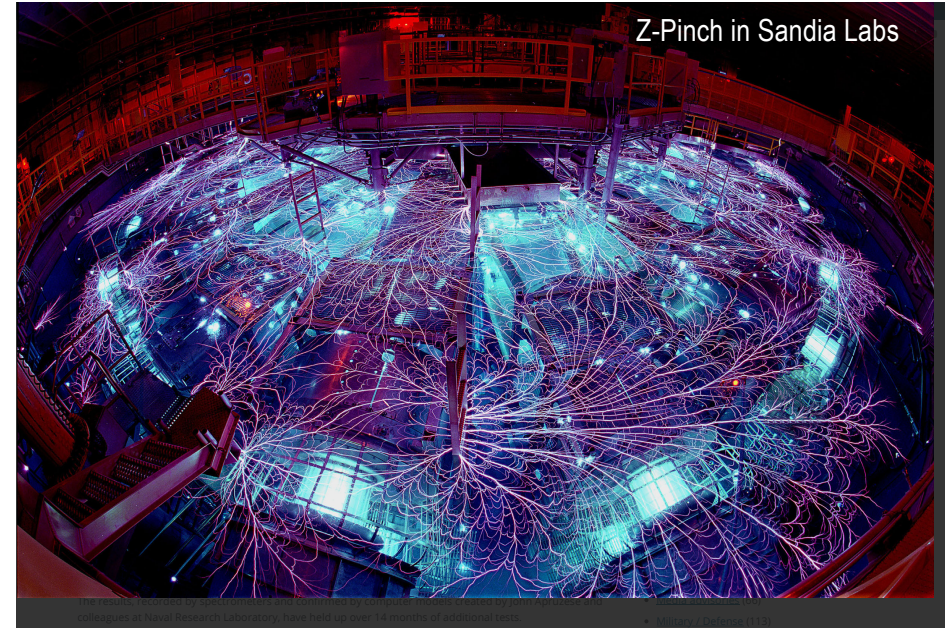


Less efficient but:
 > more stable and
 > more symmetric implosion

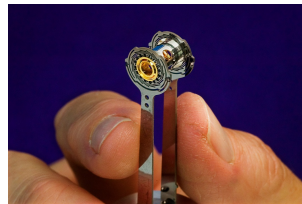
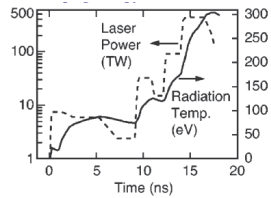
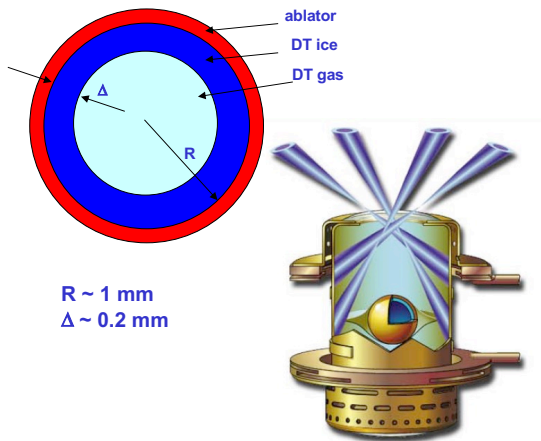
Better efficiency but:
 > less stable and
 > less symmetric implosion

Main inertial fusion facilities:
 NIF (USA) and LMJ (France)

Main Z-Pinch facility:
 Sandia Labs (USA)



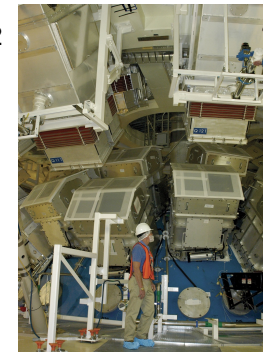
Targets for Inertial Fusion



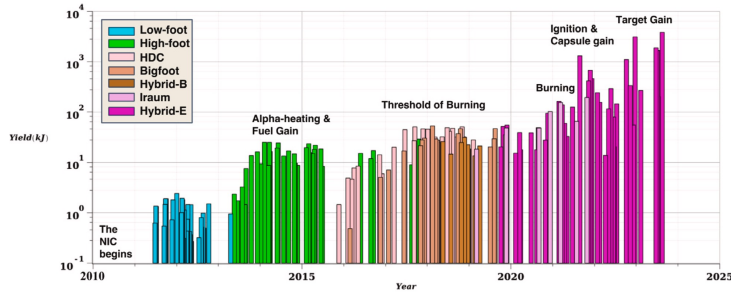
USA : National Ignition Facility (NIF)
 Livermore, California
 Experiments ongoing



in operation
 from March
 2009



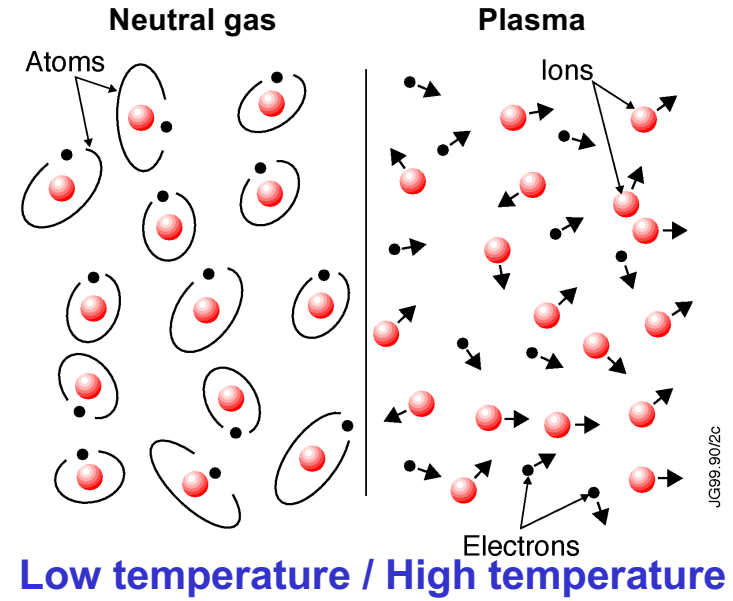
~ One experiment / week



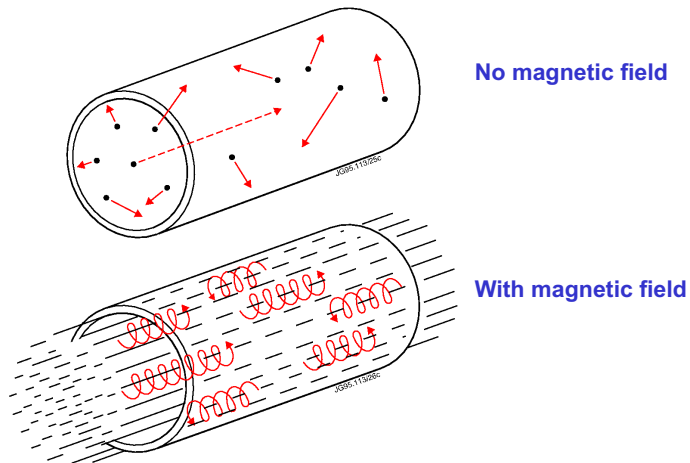
Shot	Yield (MJ)	Target Gain
Aug 2021 burning plasma shot	~1.3	<1
Dec 5 2022 ignition	3.15	1.5
Oct 2023 shot	~3.4	~1.5
Feb 2024 record shot	5.2	~2.3-2.4

Gain = $\frac{\text{Fusion energy out}}{\text{Heating energy in}}$

O.A.Hurricane, High Energy Density Physics 53 (2024) 101157



Charged particles 'stick' to magnetic field lines (Lorentz force)

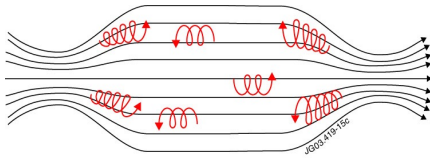


slide 36

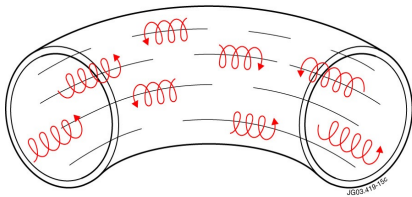
Aurora in Greifswald Monday night 19 January 2026

Particles follow magnetic fields
how to limit losses at the end of cylinder?

Two possible solutions



- 'close' magnetic field at ends
- BUT : too high losses at ends

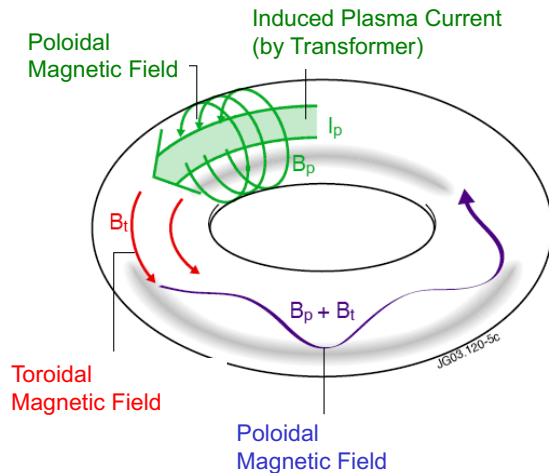


- 'close' magnetic fields on themselves
- ⇒ toroidal configuration, BUT....
- Need additional torsion for stability
- ⇒ need helicoidal magnetic field

Magnetic Fusion Machines

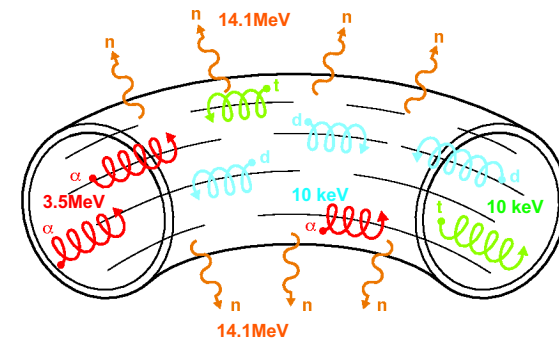
Tokamak

Large current induced in plasma (~100kA - 10MA)



Final configuration is a torus
A tube folded on itself

Charged particles are confined
Neutrons escape (carrying 80% of the reaction energy)



Helical magnetic field for stability

Note :
1 keV = 11 600 000 ° C