MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Basics of thermonuclear fusion

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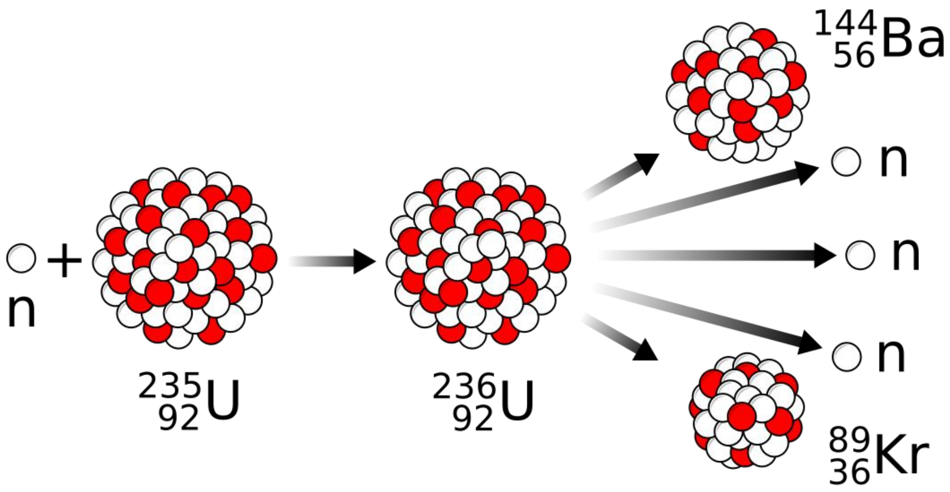
CERT Special Session on Fusion

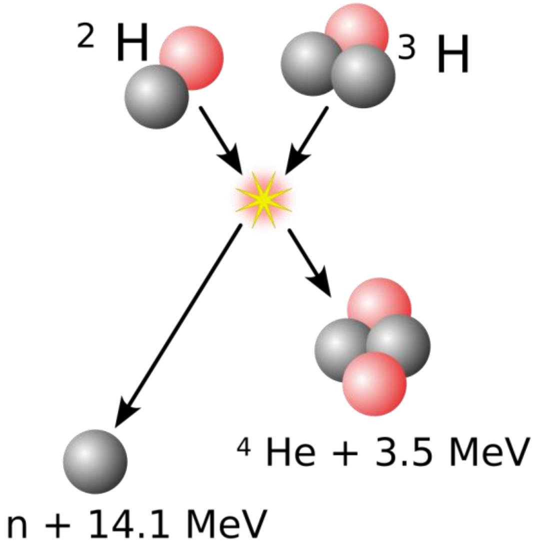
*) Emeritus

Energy gain through nuclear reactions

by liberating binding energy, which is maximum per nucleon for iron



[Source: Wikipedia]



[Source: Wikipedia]

fission of heavy nuclei

- initiated by neutrons
- propagated by neutron avalange

fusion of light nuclei

- initiated by close approach of nuclei (against Coulomb repulsion)
- at high temperatures: (> 100 Million degrees = plasma)
- propagated as thermal burn

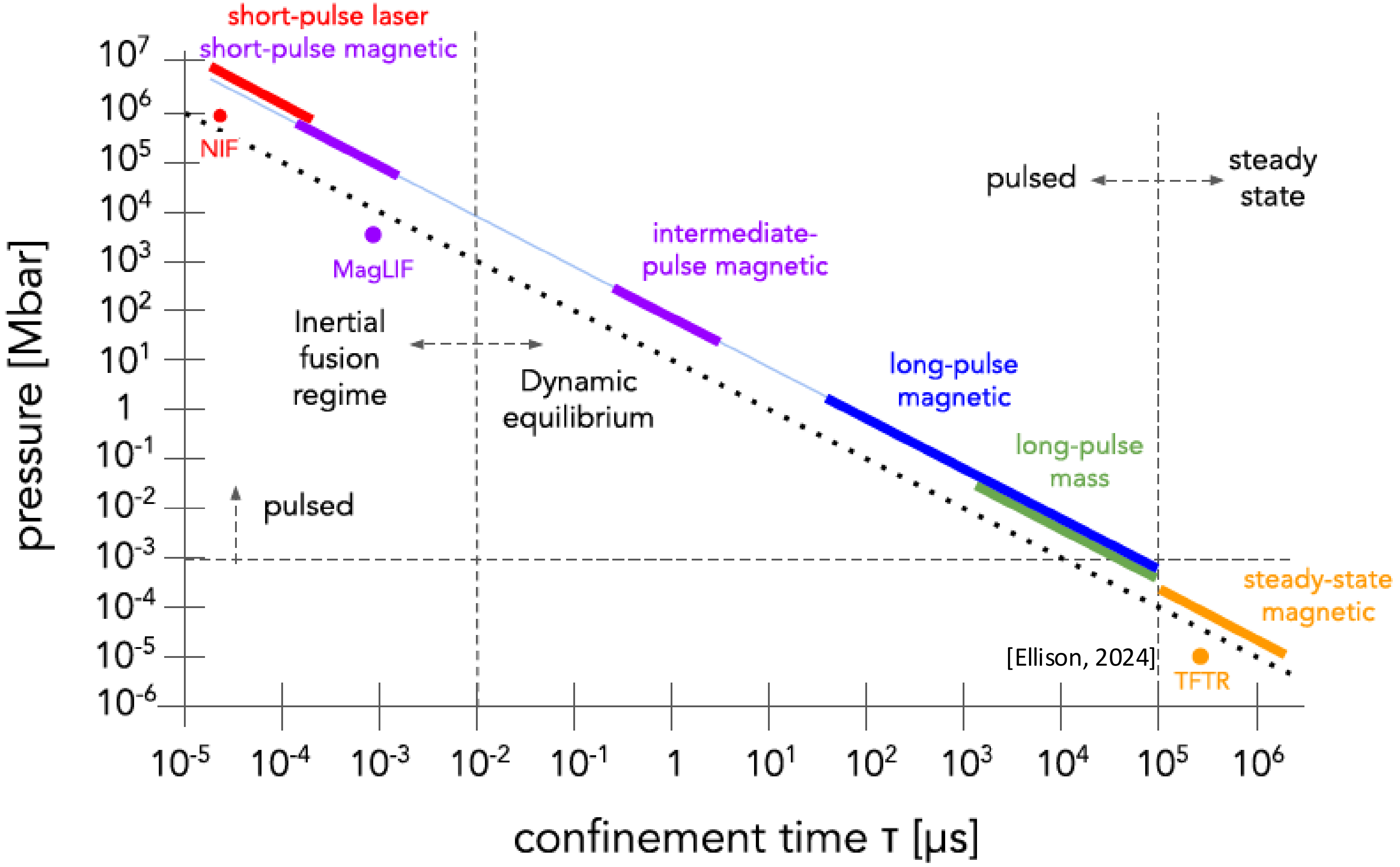
Requirements for positive energy balance

fusion energy > energy for heating: $n \cdot T \cdot \tau$ or $p \cdot \tau >$ min

time: cooling through radiation, heat conduction or: desintegration

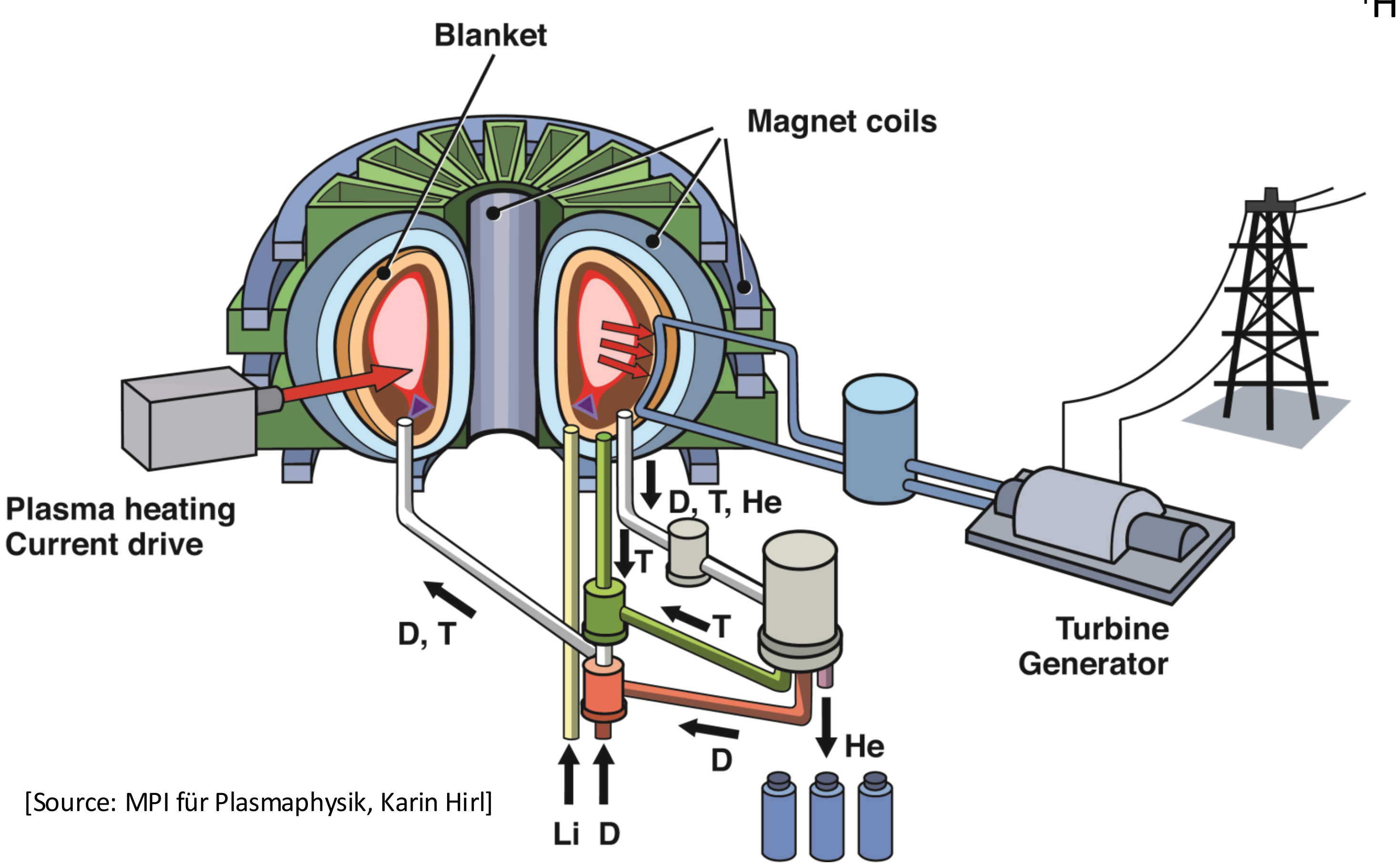
biggest success in extreme corners

for start of burn, also minimum temperature needed



A prototypical (^2H+^3H, a.k.a. D+T) fusion power plant

$^2H + ^3H$ (a.k.a. D + T) → ^4He (3.5MeV) + n (14.1MeV) + 17.6MeV



[Source: MPI für Plasmaphysik, Karin Hirl]

^4He trapped in Plasma - > (self-) heating

neutron deposited in blanket

energy for power production

particle for tritium breeding

n +^6Li → ^4He (2.1MeV) + T (2.7MeV)

radiological aspects of D+T fusion reactor

final product of DT reaction is ^4He, a stable nucleus

- no highly active fission products
- no transuranic atoms
- no runaway (cooling, fuel supply limited to couple of minutes)

radioactive intermediate product tritium: beta radiator, 12.3 yrs half-life → inventory control
fuel-cycle and blanket technology

activation of structures – issues of radioactivity and structural integrity → material development

why not alternative – (aneutronic) - fuels?

$D + {}^3He \rightarrow {}^4He\ (3.7MeV) + p\ (14.6MeV) + 18.3MeV$

$p + {}^{11}B \rightarrow 3\,{}^4He + 8.7MeV$

- desireable properties, but much higher (unrealistic?) demands on T and $nT\tau$
- no terrestrial supply of ^3He (requires neutronic breeding via DD-fusion

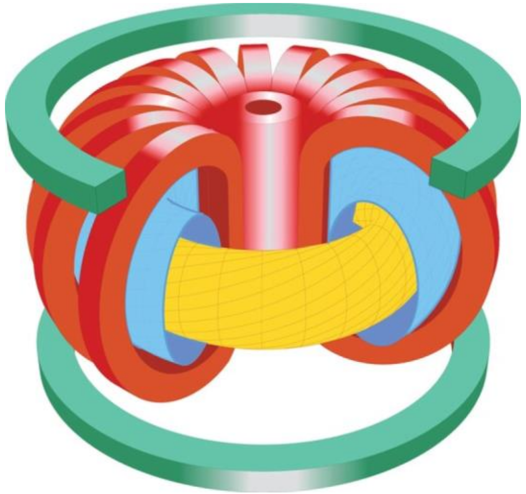
[Lackner]

Parameter\Reaction	D-T	D-He³	D-D	H-B¹¹
optimum composition for maximum fusion power at given pressure (Te=Ti)	1:1	3:2	1:1	3:1
maximum fusion power density at constant pressure (rel.units)	1,00	0,02	0,04	0,0013
maximum ratio $\langle\sigma v\rangle/T^2$	1,00	0.022	0.013	0,008
burn temperature[keV] optimized for power density at given pressure	15,00	50,00	20,00	140,00
minimum required $n T\tau$ for ignition (rel.units)	1	11	16	100

Dominant approaches to thermonuclear fusion

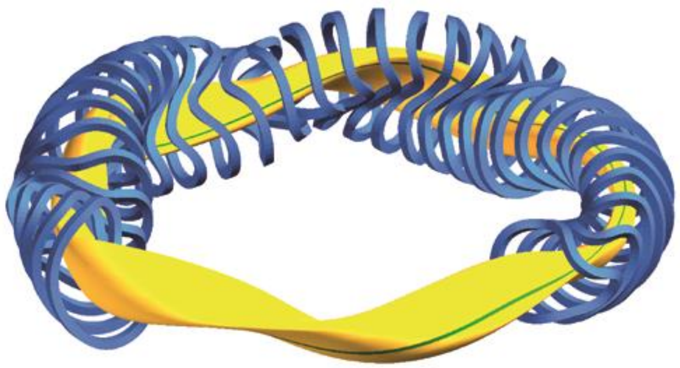
(quasi) steady-state magnetic confinement:

Tokamak



particles and field lines stay on closed „flux“ surfaces

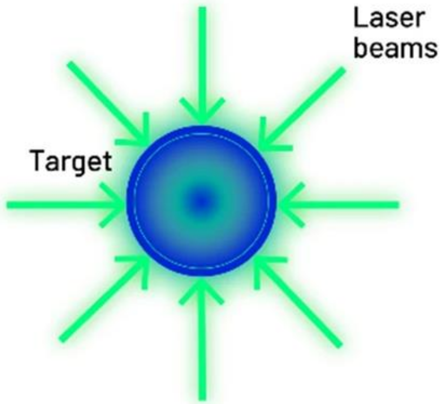
Stellarator



[Source: MPI für Plasmaphysik]

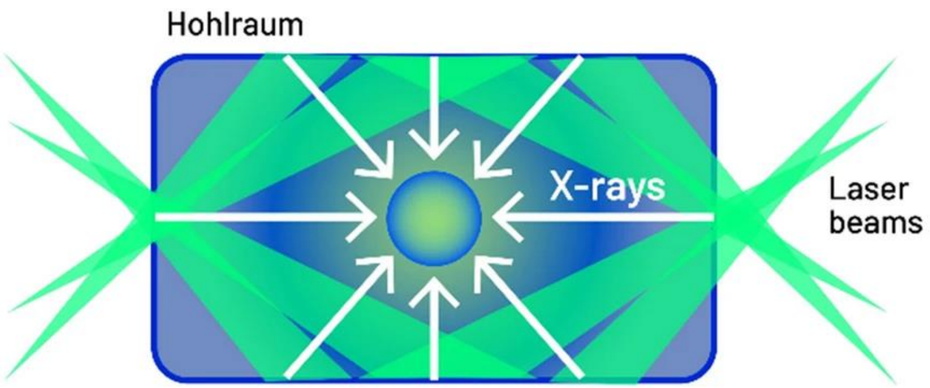
inertial confinement:

Direct Drive



laser light ablates material recoil compressed and heats fuel

Indirect drive



[Ditmire, 2023]

State of art and recent progress

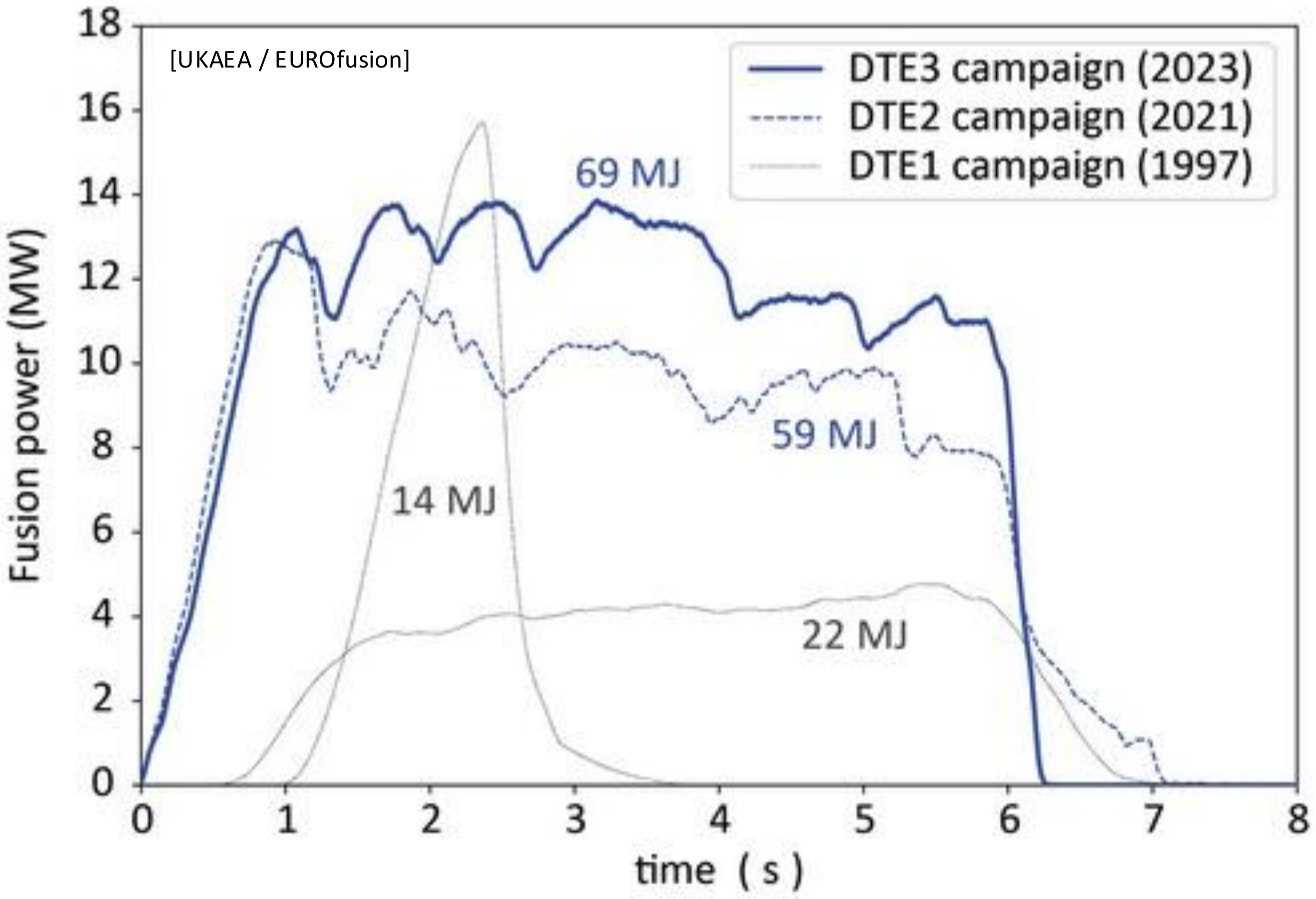
(quasi)steady-state magnetic confinement: - focus on developing reactor relevant solutions

thermonuclear burn only secondary aim
(TFTR, JET)

- control of impurities: divertor concept and conversion of power into electromagnetic radiation (ASDEX-Upgrade, DIII-D, JET)

- quasisteady state operation with current drive and
- superconducting magnet (KSTAR, EAST, WEST)

- quasisteady operation without net plasma currents and superconducting magnets (Heliotron, W7-X)



Fusion Energy Production on JET

$$Q_{target} = P_{fusion}/P_{injected} = 0.35$$

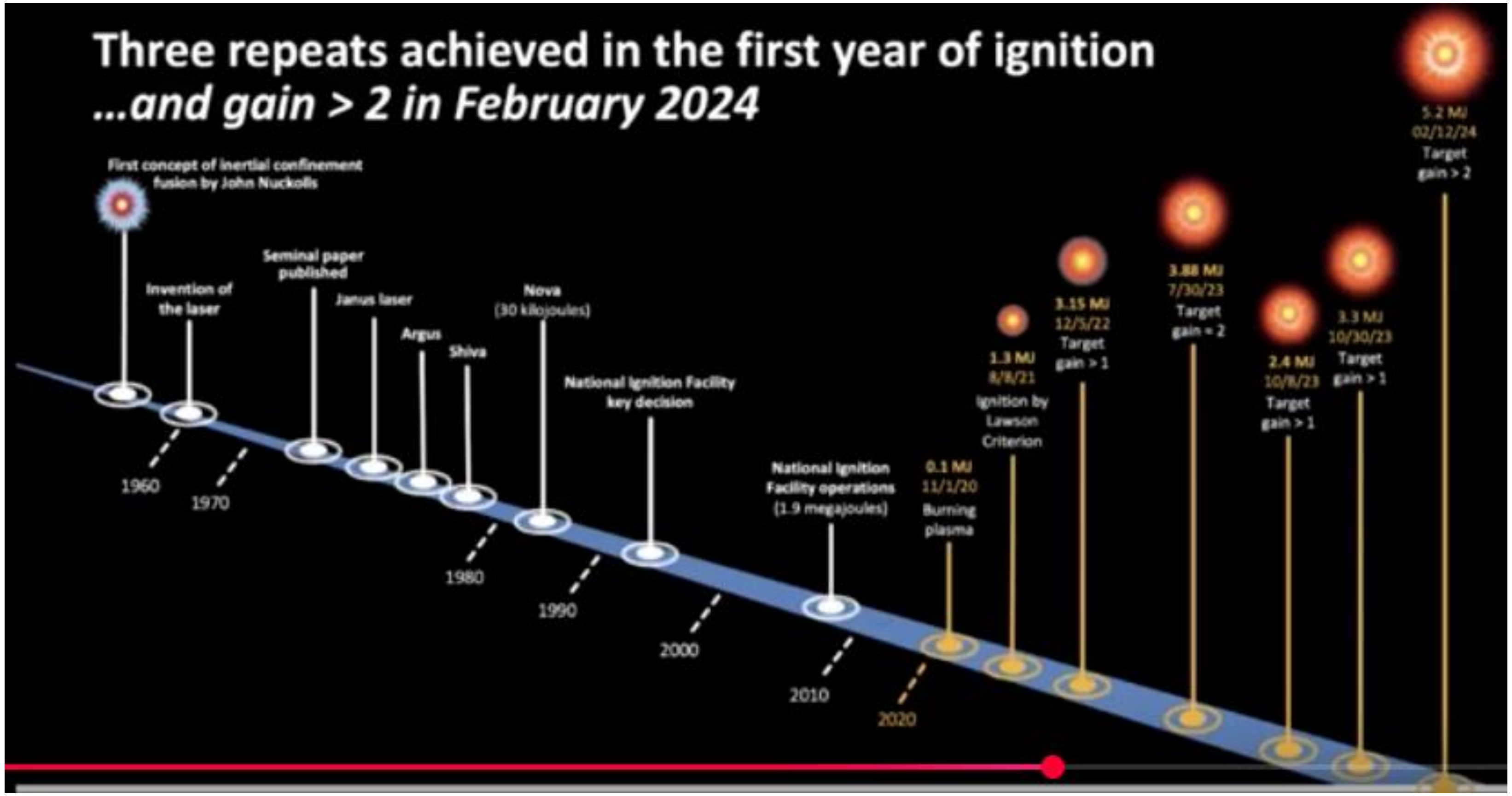
State of art and recent progress

inertial confinement:
achievement of ignition

(NIF`s Mission Statement)

- Stockpile stewardship
- Discovery science
- Achieving ingnition and inertial confinemen fusion

Fusion Energy Production at NIFs



[Schlossberg, 2024]

$$G_{target} = E_{fusion}/E_{Laser} > 2$$

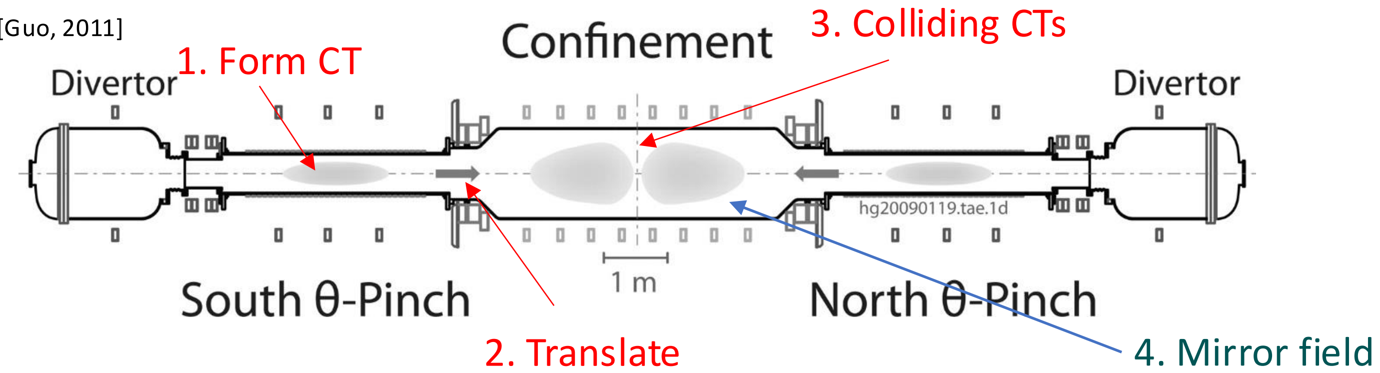
Start-ups and alternative approaches

tokamak or stellarator or NIFs-concept based approaches, taking a higher risk (Commonwealth Fusion, Tokamak Energy,..Proxima Fusion, Type One Energy.., Focused Energy,..):

- using less established technologies (high temperature/high-field superconductors)
- extrapolate into less explored areas of experimental data base (spherical tokamaks, turbulence-minimized stellarators)

reviving abolished concepts due to game-changing discoveries/technologies (intermediate pressure/lifetime regime)

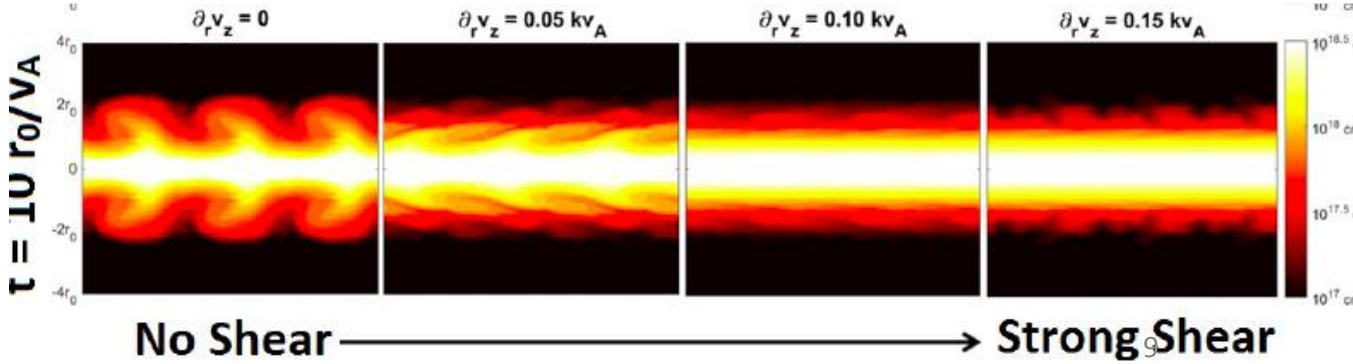
[Guo, 2011]



colliding FRCs (TAE, Helion)

[Shumlak, IAEA 2020]

shear-flow stabilized Z-pinches (ZAP)

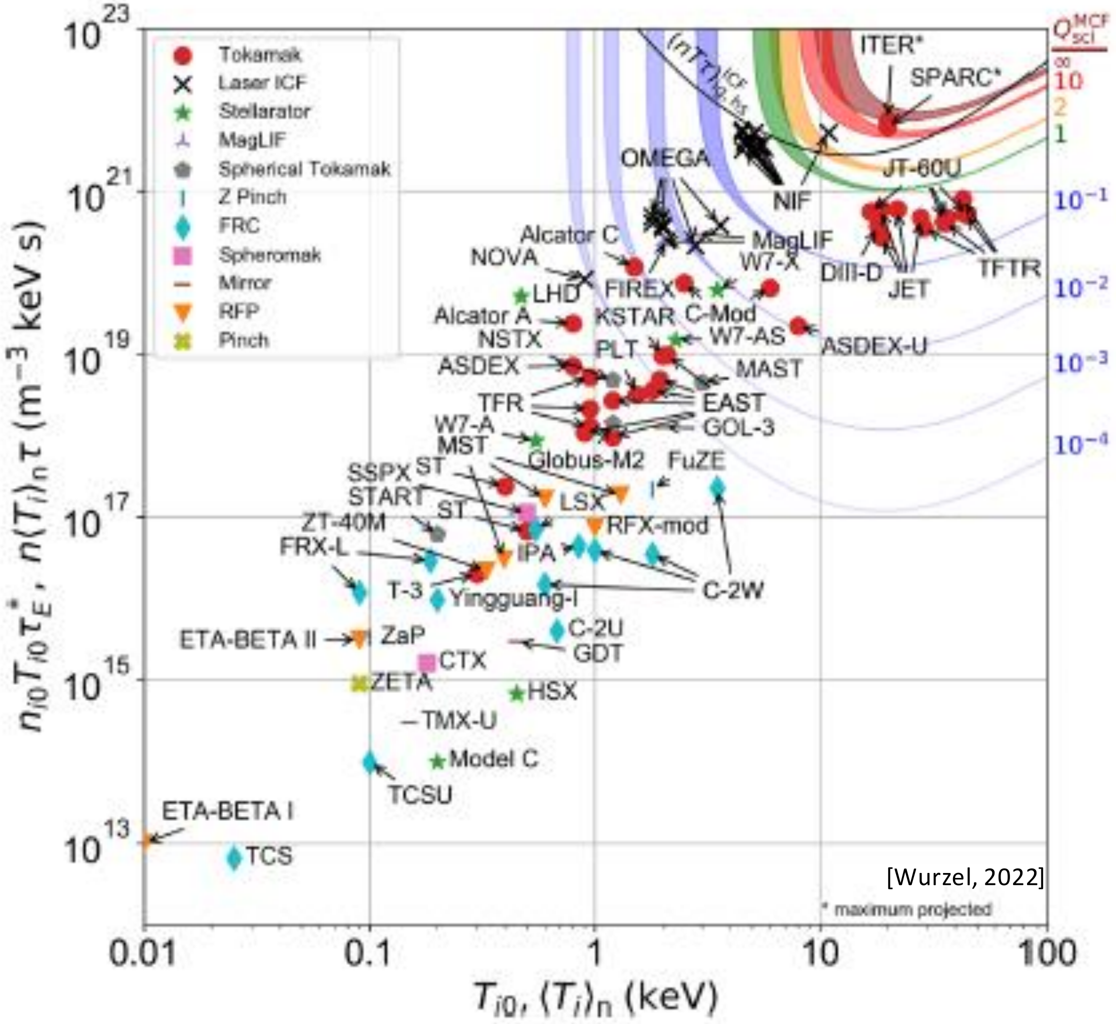


A look back

❖ **(Mainstream) Fusion Experience**

- fusion (even alone physics) is a multifaceted problem
  1. equilibrium /macroscopic stability
  2. thermal insulation (confinement)
  3. plasma wall interaction
     - first only viewed from plasmas: impurities
     - now from wall: survival
  - ……… heating, confinement of α-particles

- can generally be addressed only sequentially
- stellarator and tokamaks are survivors and compromises: solutions - non-optimal - to all of them



Outlook: magnetic confinement

a clear default path to a reactor exists

based on scaling up existing physics to ITER

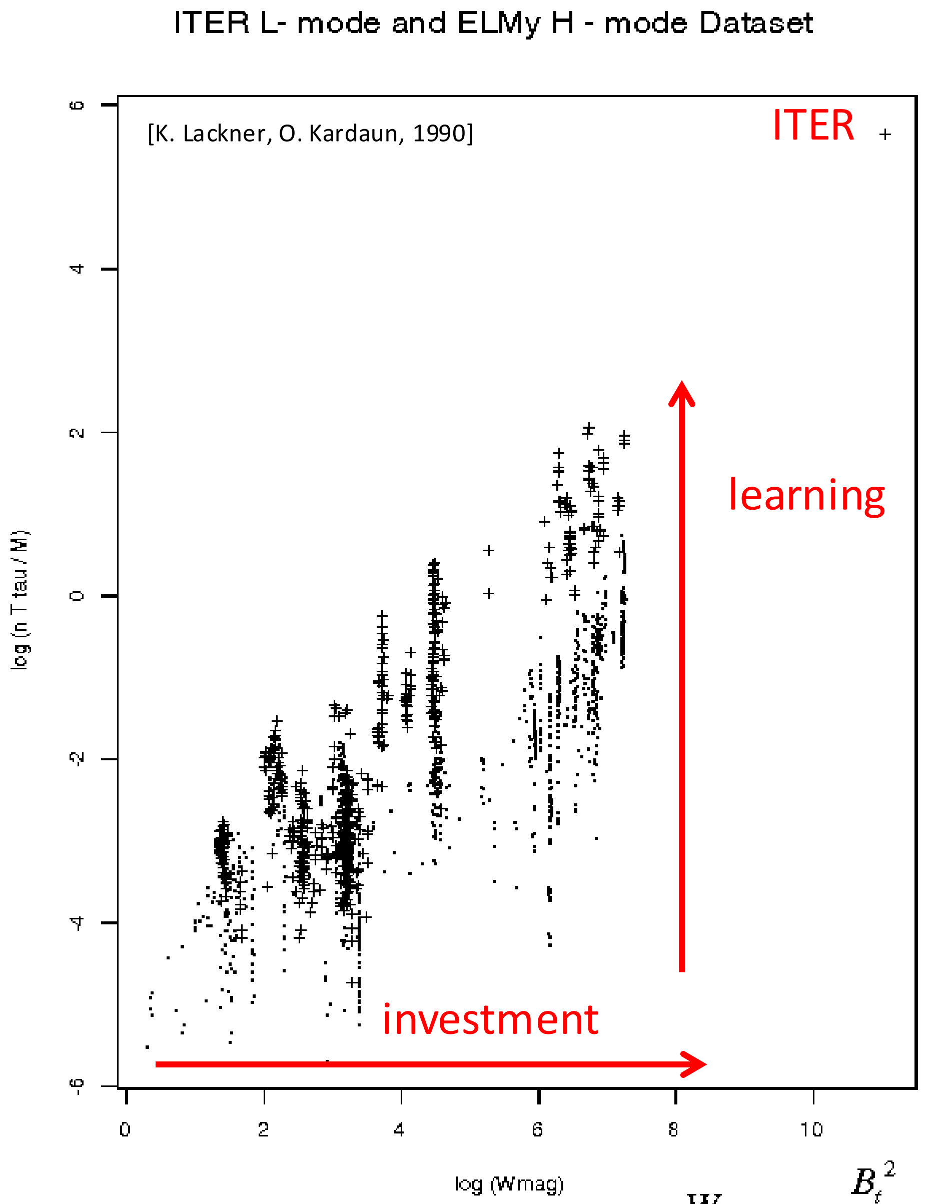
compatible with power plant technologies

- blanket technology
- fuel cycle
- power extraction
- magnet technology
- heating and current drive

material issues

- low activation strutural
- heat load handling

possible alternatives



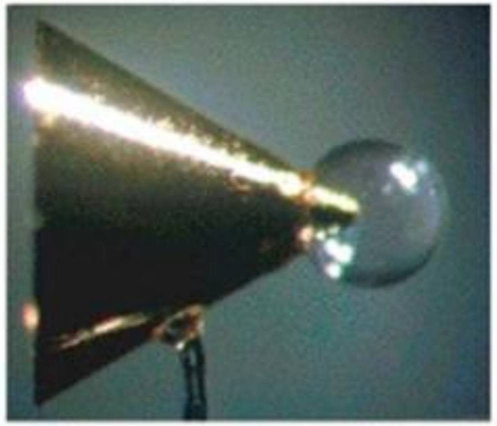
$$W_{magn} = \frac{B_t^2}{2\mu_o} \cdot V$$

Outlook: inertial confinement

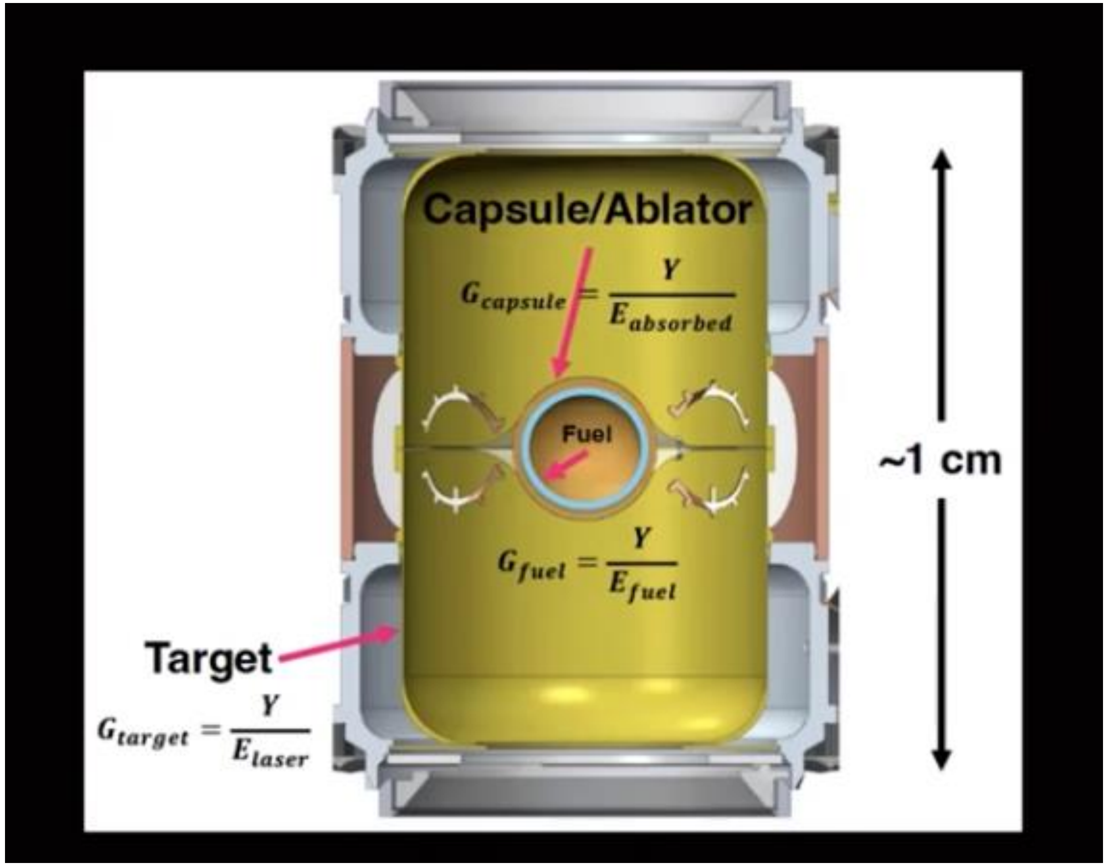
milestone of target gain >1 has been reached

but probably qualitatively different path for reactor needs to be developend

- direct drive
- e.g. fast ignitor



[IAEA Fusion Physics Chapter 10: Mima]



[Schlossberg 2024]

power plant components only at level of conceptual ideas

economic driver (laser) development

economic target fabrication

material issues and fuel cycle (synergies with MCF)

$G_{target} \sim 1.5$, $G_{capsule} \sim 12$, $G_{fuel} \sim 160$

Sources of figures:

Fission: https://de.m.wikipedia.org/wiki/Datei:Nuclear_fission_reaction.svg

Fusion: https://de.wikipedia.org/wiki/Kernfusion#/media/Datei:Deuterium-tritium_fusion.svg

Schlossberg,D: https://www.pppl.gov/events/2024/science-saturday-remarkable-story-fusion-ignition-national-ignition-facility-david (2024)

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