Fusion power plant concepts

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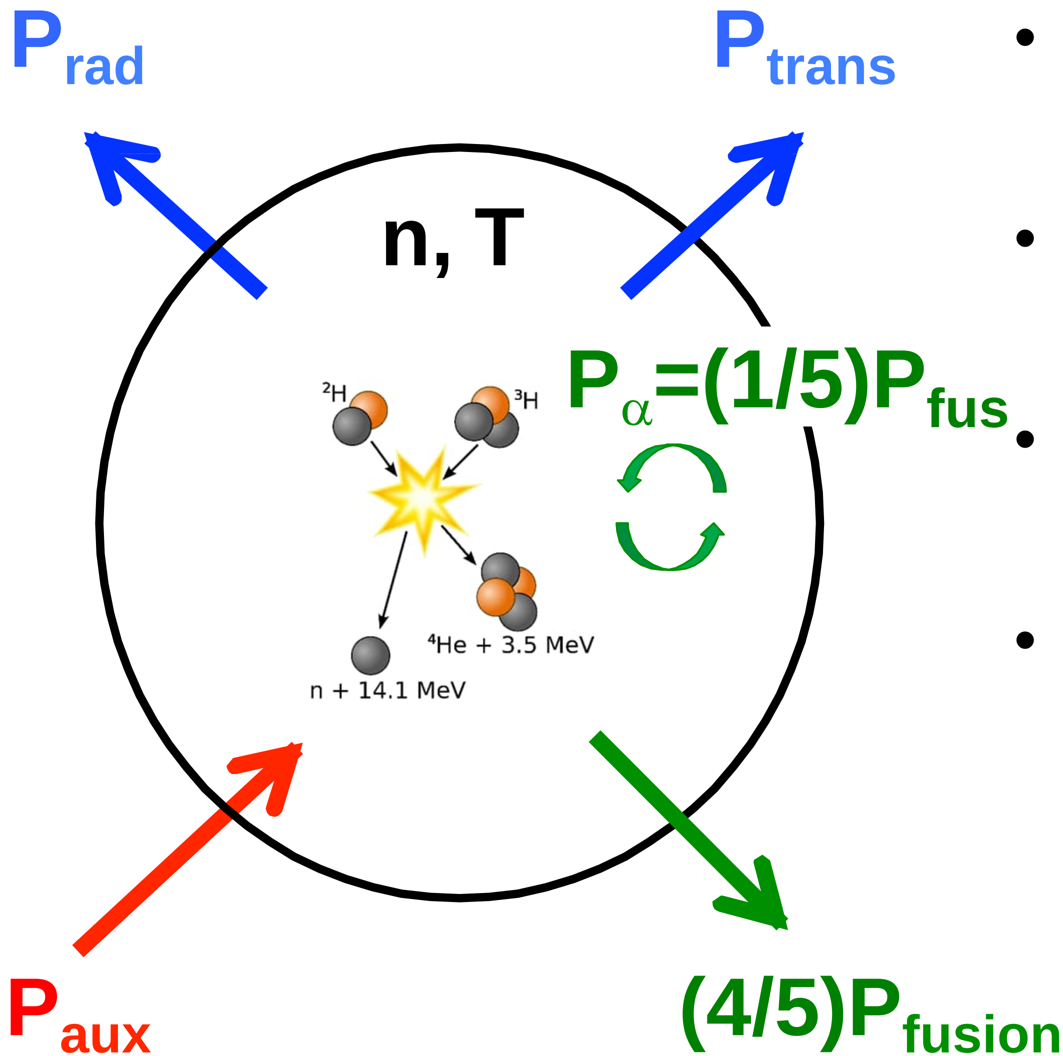
Outline

- **Introduction of concepts for possible (thermonuclear) fusion devices ⇒ past, current, and future plants**
  - Tokamaks ⇒ ITER and DEMO
  - Stellarators ⇒ Wendelstein 7X and HELIAS
  - Laser devices ⇒ NIF

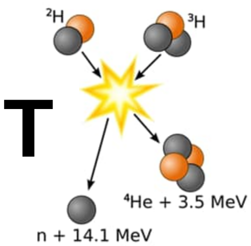
The triple product gives the required plasma density, temperature and confinement for break-even



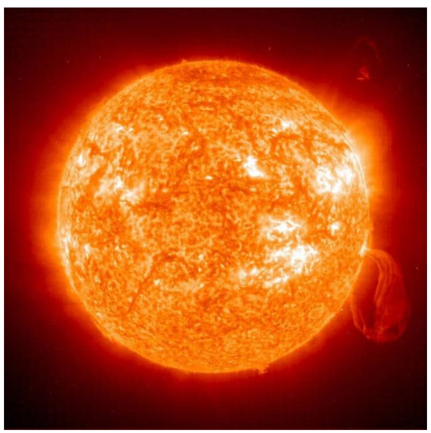
- Internal heating via fusion α's (> 1 MeV)
- Fusion power in neutrons
- Radiative and transport losses
- Up to self-sustained burn, auxiliary heating required ⇒ fraction of P_{fusion}

Fusion plasmas may be confined with gravity, magnets, or inertially with lasers

n, T

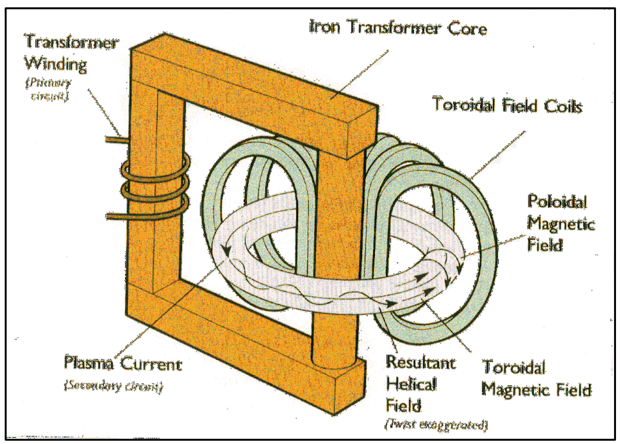


Gravitation



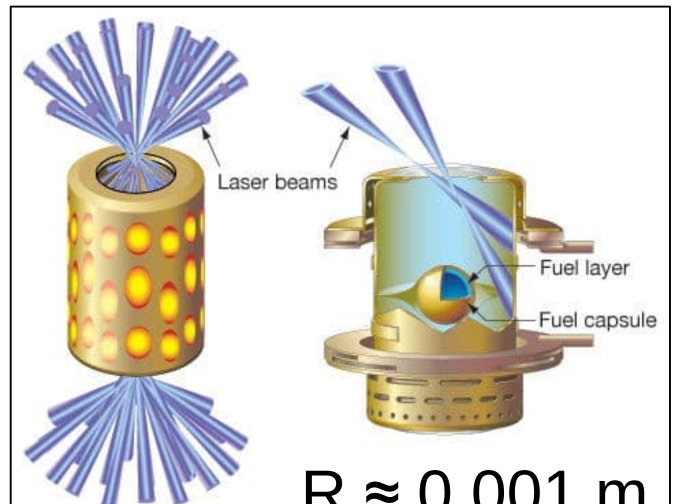
R = 0.7 x 10^9 m

Magnetic confinement



R < 10 m

Inertial confinement

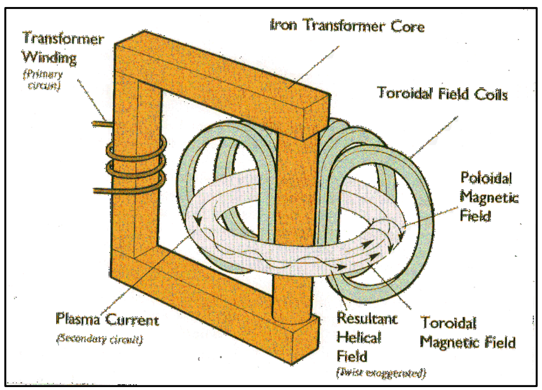


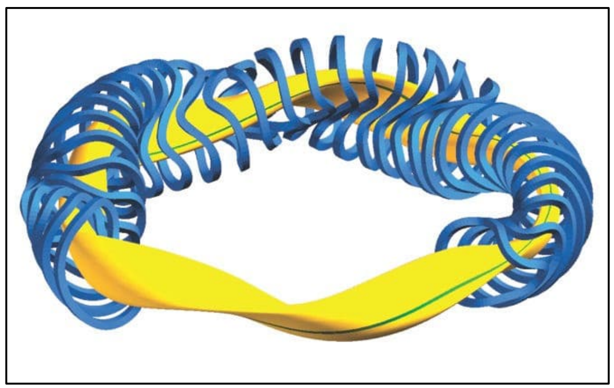
R ≈ 0.001 m

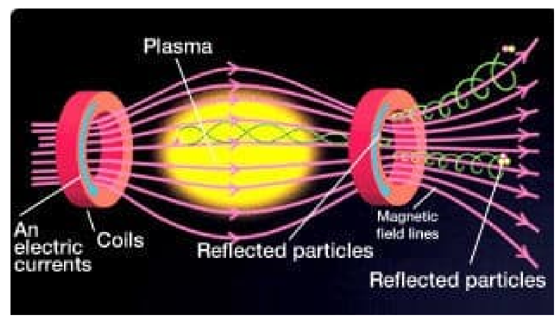
The most promising magnetically confined concepts are tokamaks and stellarators

Magnetic confinement

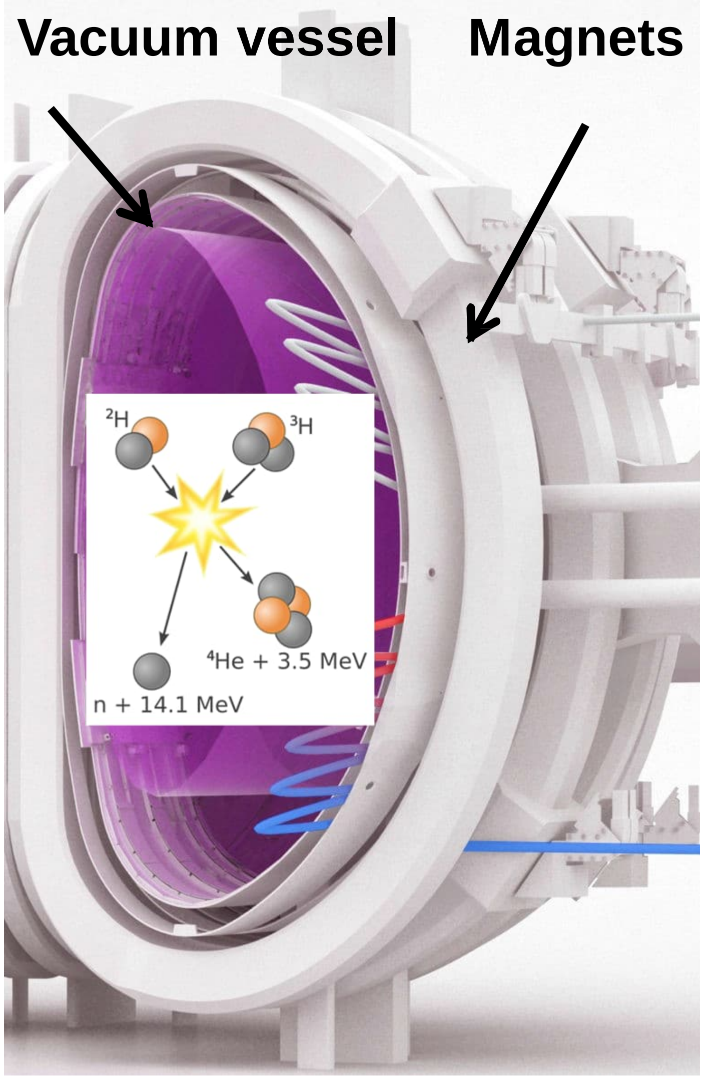
Tokamaks	Helical systems/ Stellarators	Mirrors/ spheromaks/ Field reversed configs.







In tokamaks, conditions close to break-even have already been achieved

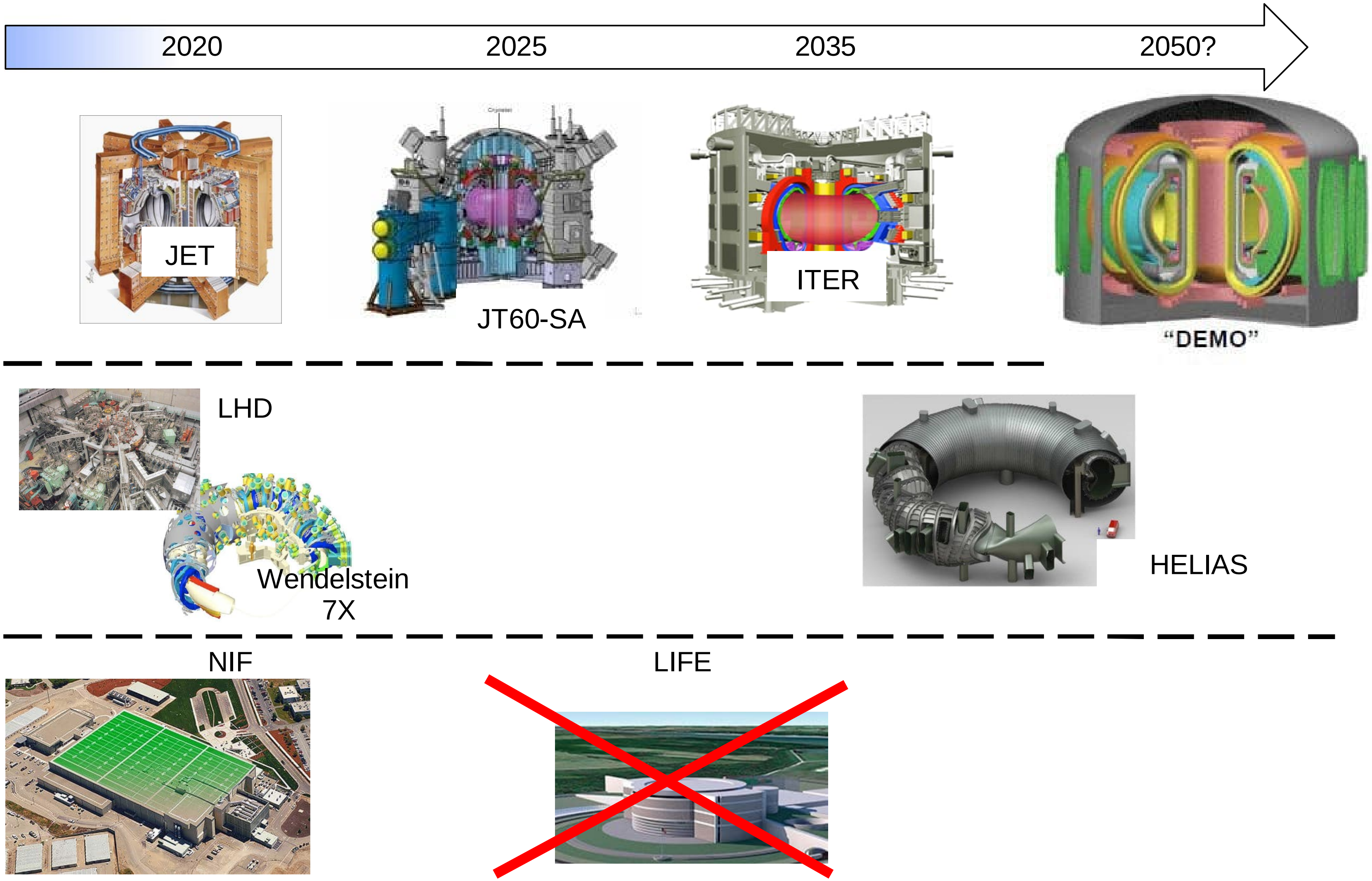


- **Vacuum vessel surrounded by magnets**
- **D-D and D-T plasmas**
- **Plasma conditions:**
  - Plasma temperature > 10 keV
  - Fuel density ≥ 10^{20} m^{-3}
  - (Energy) confinement time > 1s

$$\Rightarrow (nT\tau_E)_{exp} \approx 10^{21}\ \text{keV s m}^{-3}$$

$$\leq (nT\tau_E)_{break\text{-}even}$$

The world-wide fusion effort runs along three concepts: tokamaks, stellarators, and lasers

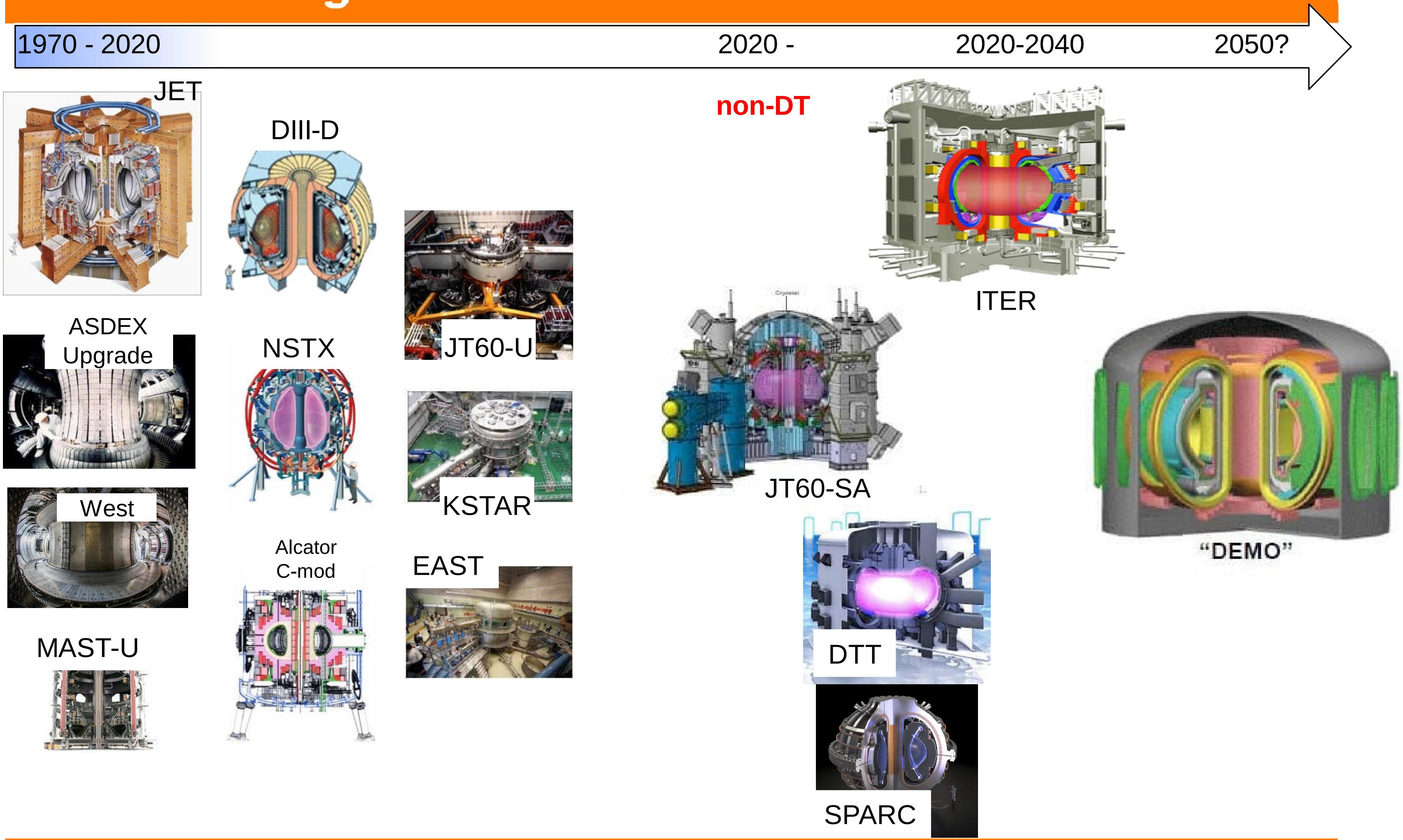


The world-wide fusion effort runs along three concepts: tokamaks, stellarators, and lasers

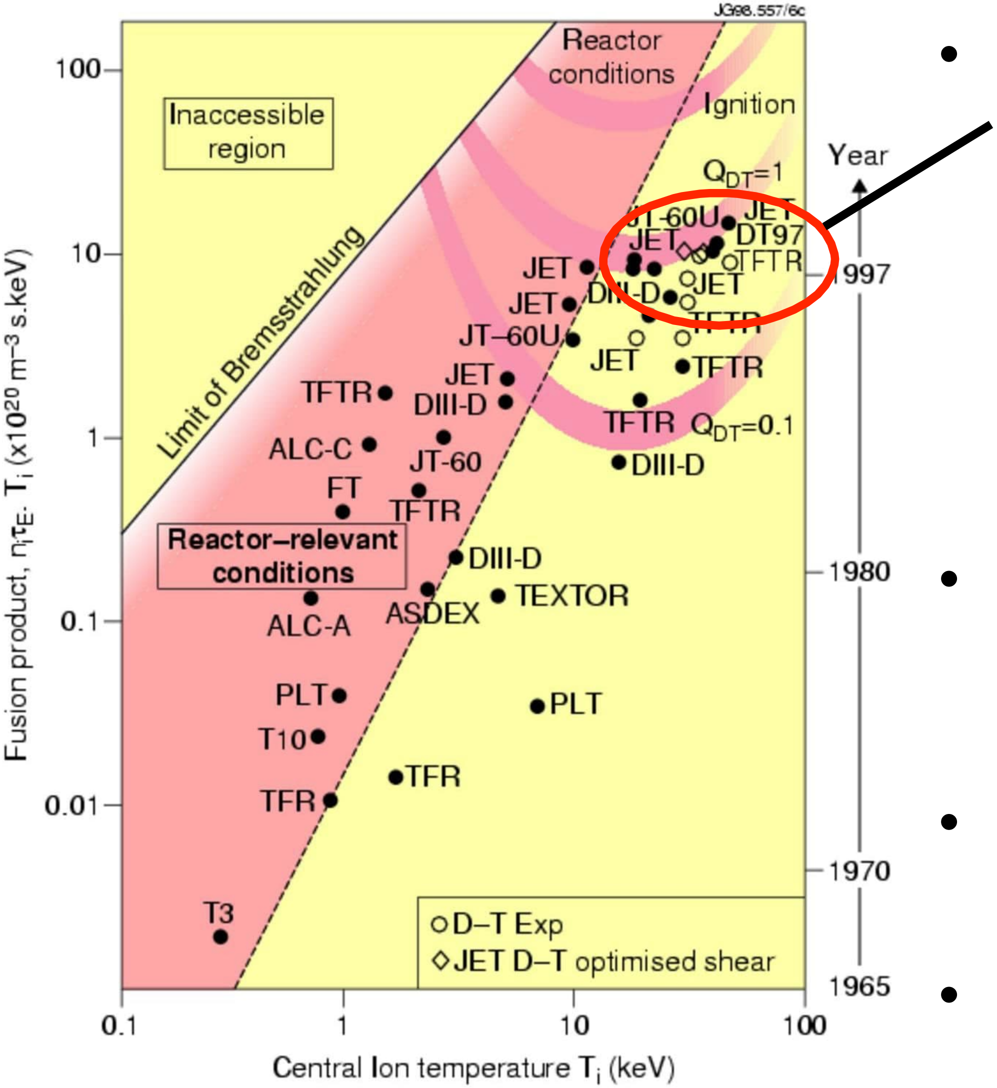
	Tokamaks	Stellarators	Lasers
Plasma stability	Large plasma currents ⇒ Disruptions	Current-free	Implosion physics, hydrodynamic instabilities
Steady-state	Pulsed, steady-state up to 1000s	Inherently steady-state, high plasma pressure	Pulsed (at ~1 Hz)
Fusion performance	2/3 of break-even	Factors of 2-5 less than tokamaks	Reached scientific break-even (12/2022)
Critical technology	Instability control; fusion materials	Complex coil system; fusion materials	Large laser devices (GWs), target materials

Tokamaks

Tokamaks are currently the front-runners for a reactor design

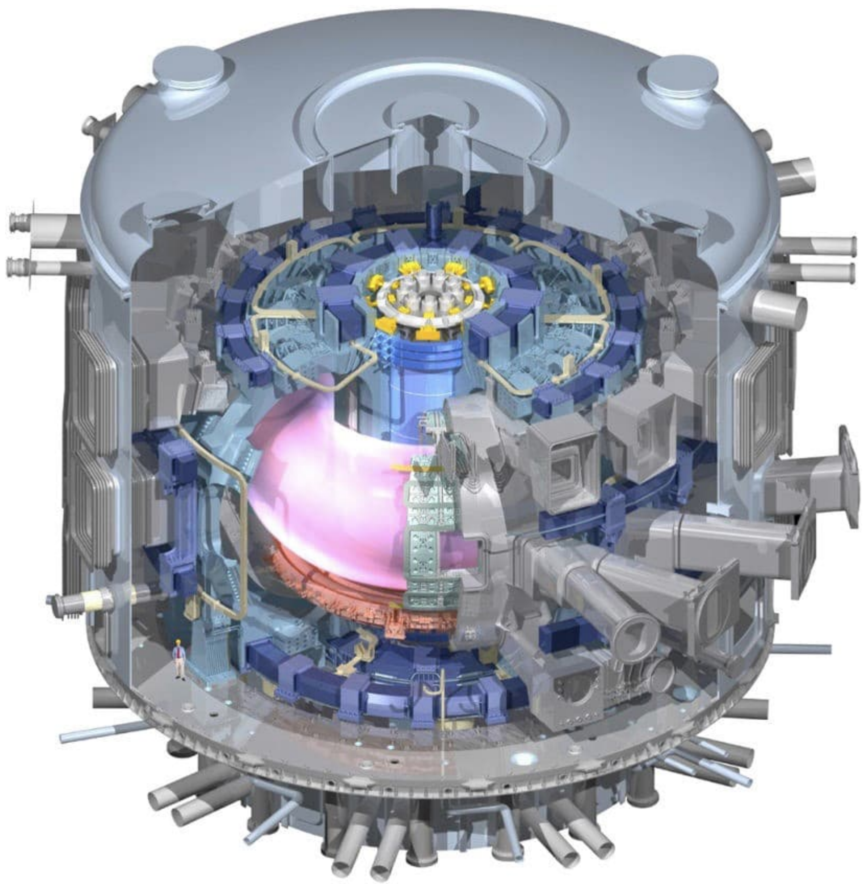


Fusion performance in tokamaks has been pushed close to break-even ($P_{fus} \approx P_{aux}$)



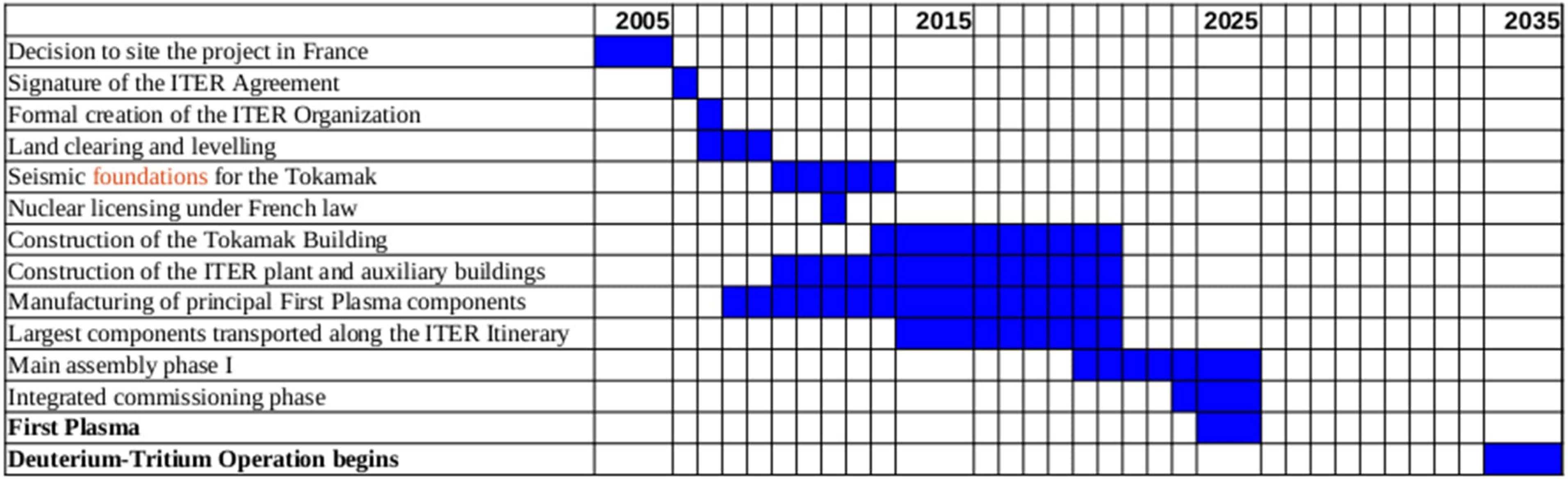
- **Cluster of high- performance pulses in the late 90s w/ carbon-based walls ⇒ JET ITER-like wall + DTE2 2021 → new record: stable plasma releasing 59 MJ of energy (PR 9.2.2022)**
- **Performance limited by MHD and available auxiliary power ⇒ tritium retention**
- **⇒ "The bigger the machine, the better the performance"**
- **⇒ Reactor-size fusion devices large: ITER, DEMO**

ITER will be the world's first burning-plasma experiment to be operated in the 2030s



	JET	ITER
Size	3 m (15 x 15m)	6.2 m (30 x 30m)
Toroidal magn. field	3.4 T	5.3 T
Plasma current	5 MA	17 MA
P_{aux}	38 MW	50 MW
P_{fusion}	16 MW	500 MW
dpa		1 / 20 yrs

ITER will be the world's first burning-plasma experiment to be operated in the 2030s



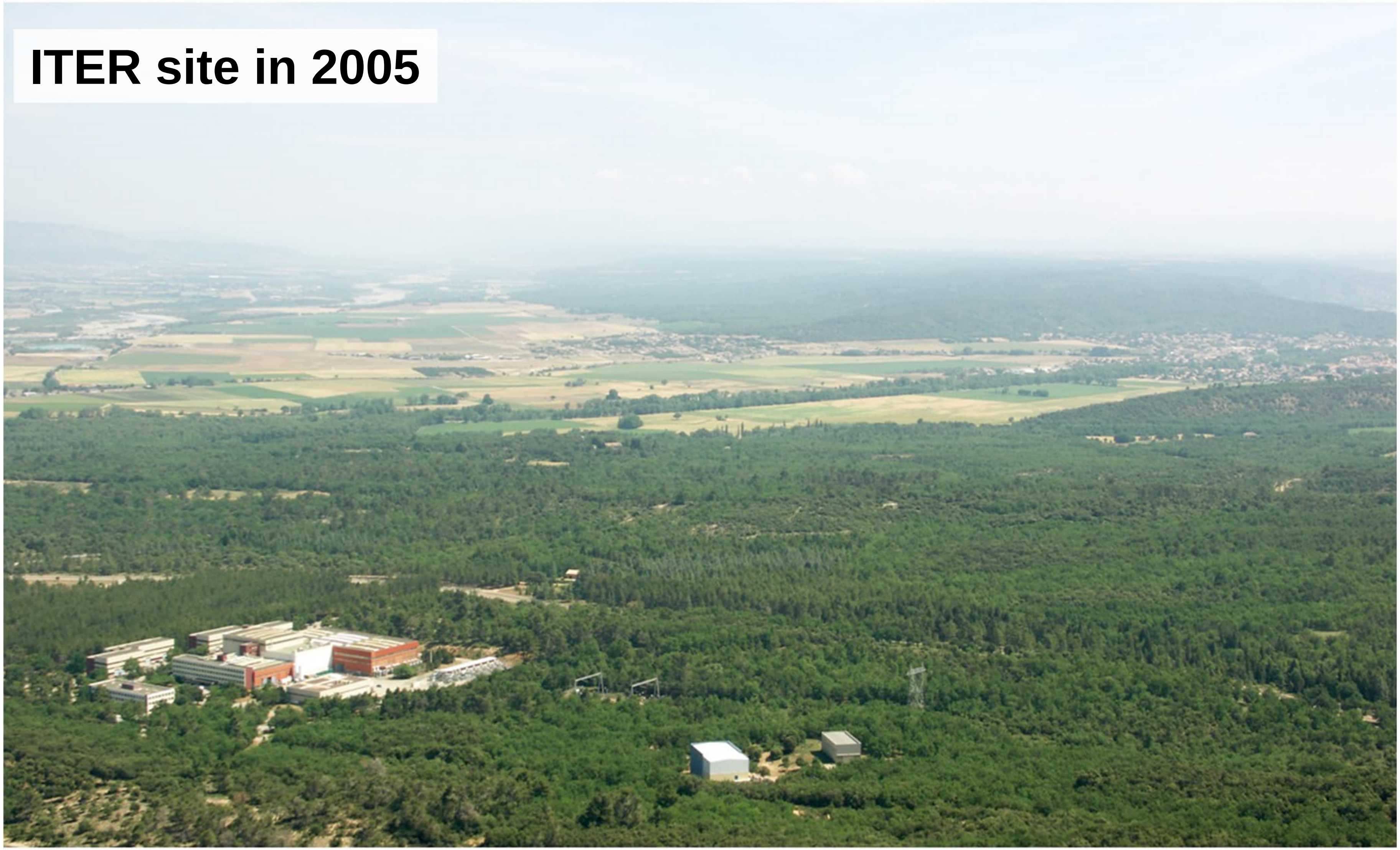
- **First plasma 2025 and operation in D-T is currently planned to start in 2035 (ITER press release Nov 17, 2016). Delays still possible…**

ITER time scales have been and are also driven by politics rather than science and technology

- **1985: Concept of the ITER Project was conceived at Geneva Summit between Reagan and Gorbachev**
- **1998: US leaves the ITER project**
- **2003: US rejoins the project**

- **The ITER Agreement signed in 2006 (six parties)**
- **2022: "77.7% completion to first plasma" (ITER webpage, Oct 31, 2022)**

ITER will be the world's first burning-plasma experiment to be operated in the 2030s



ITER will be the world’s first burning-plasma experiment to be operated in the 2030s

Six years of steady progress

Bigot, Fusion Power Associates, Dec 2020

November 2014

November 2020

More than 75% of the installation’s civil works are now completed.

ITER-video

ITER – getting close every day (drone video 3:21)

https://www.iter.org/news/videos/601

Goal: to get general idea of construction of ITER

DEMO is expected to be a long-pulse device (~hours) and GWs output

- **Still in conceptual design phase! E.g. DEMO-CREST based on ITER at P_{fus} = 10x P_{aux}; ARIES-AT, EU PPPT (there can be several DEMOs)**
- **Escalated engineering challenge compared to ITER:**
  - Fusion material and their limits: neutron fluxes (up to 100 dpa/yr vs 1/20 for ITER)
  - Real-time control of power exhaust (~100 MW) and real-time plasma burn control (e.g., 50-50 mix)
- **Fusion will go from a science-driven, lab-based exercise to an industry-driven and technology-driven program**
- **Key criterion for DEMO is the production of electricity, although not at the price and the quantities of commercial power plants**

DEMO is even more challenging than ITER

- **Large enough P_{fus} needed to produce sufficient net electricity**

⇒ **Large outflow of power from core (P_{sep}) to first wall ⇒ excessive heat flux leading to damage**

⇒ **Operation at a higher core radiation fraction than in present-day experiments and ITER**

	ITER (R=6.2 m, P_{tot}=120 MW)			DEMO (R=8.5 m, P_{tot}=400 MW)		
	P_{sep} [MW]	P_{LH} [MW]	$P_{rad,core}$ [MW]	P_{sep} [MW]	P_{LH} [MW]	$P_{rad,core}$ [MW]
lower bound	43	~ 70	77 (64%)	60	~100	340 (85%)
upper bound	93	~ 70	27 (22%)	125	~100	275 (70%)

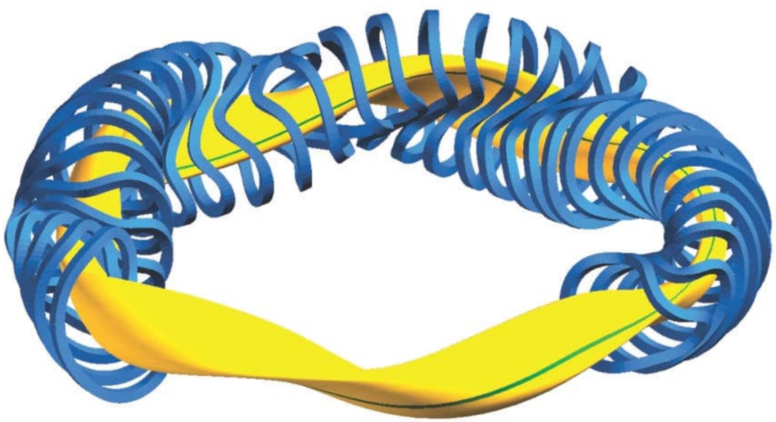
Presemo quiz #1

https://presemo.aalto.fi/fet/

Stellarators

Stellarators are current-free devices and thus inherently steady-state

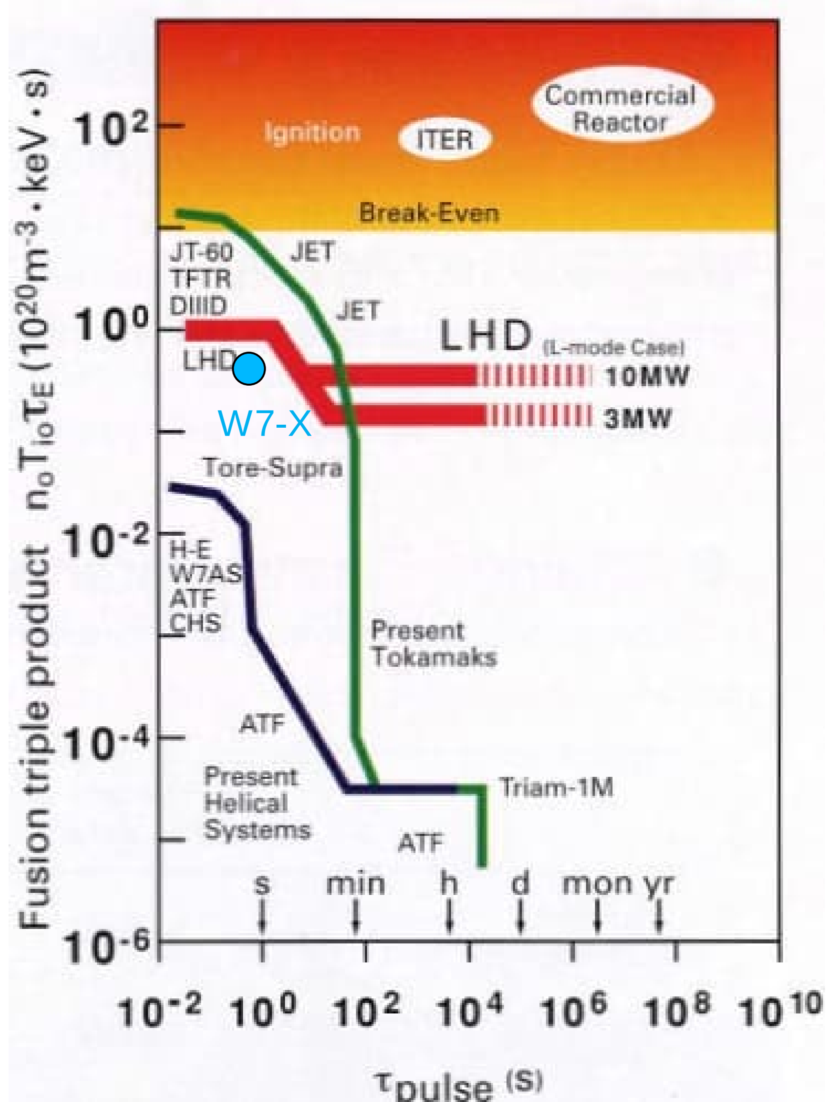
- **In tokamaks, abrupt loss of plasma current leads to disruption ⇒ loss of GJs in plasma and magnetic energy to surrounding walls on 1 ms time scale**



- **In stellarators, shaping of the magnetic coils to confine the plasmas**

⇒ Coil system of latest- generation stellarators are designed based on optimizing the magnetic topology

Large Helical Device (LHD, R=3.6 m) was the world's largest stellarator project (before W7-X, R=5.5m)



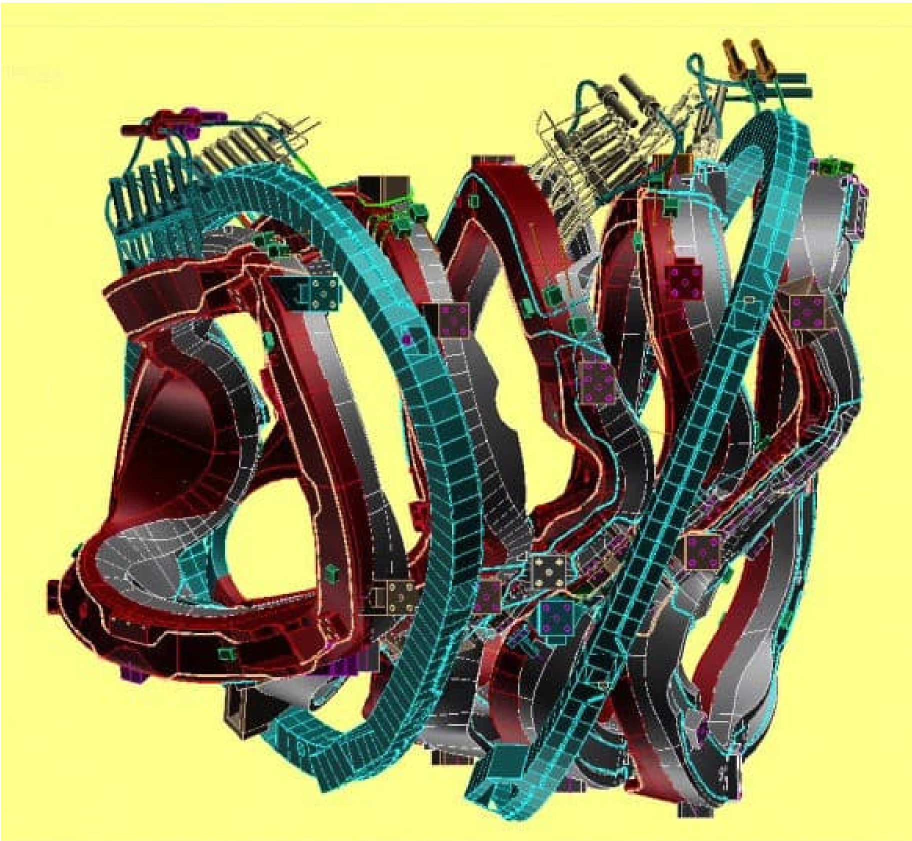
- **Plasma performance is ~2-5x lower than in tokamaks**

⇒ Improvement of performance is expected by even more complex coil design ⇒ W7-X

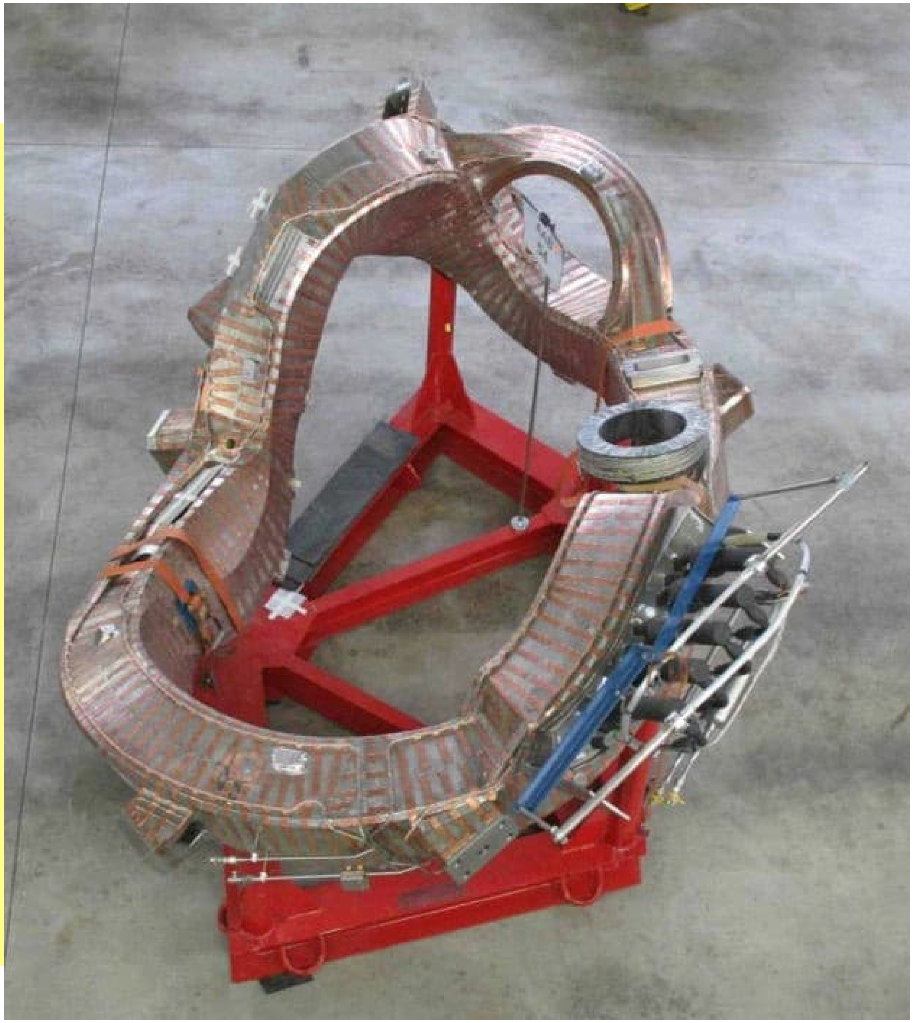
http://www.lhd.nifs.ac.jp

Design and fabrication of non-planar coils, and integration thereof are a major engineering effort

CATIA design of several coils for a stellarator (W-7X)

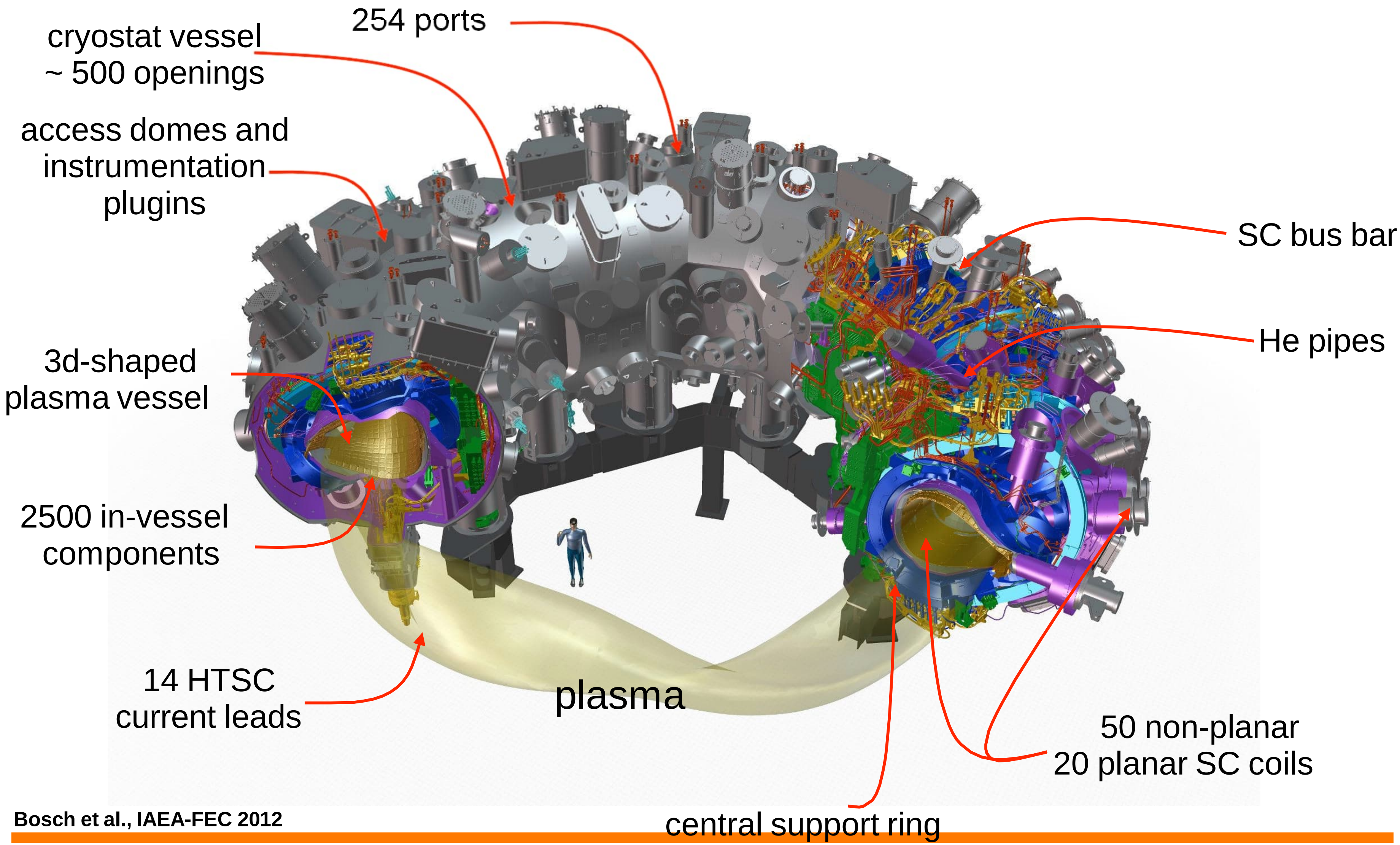


Fabricated prototype coil



Klinger et al., presentation to ITER 2012

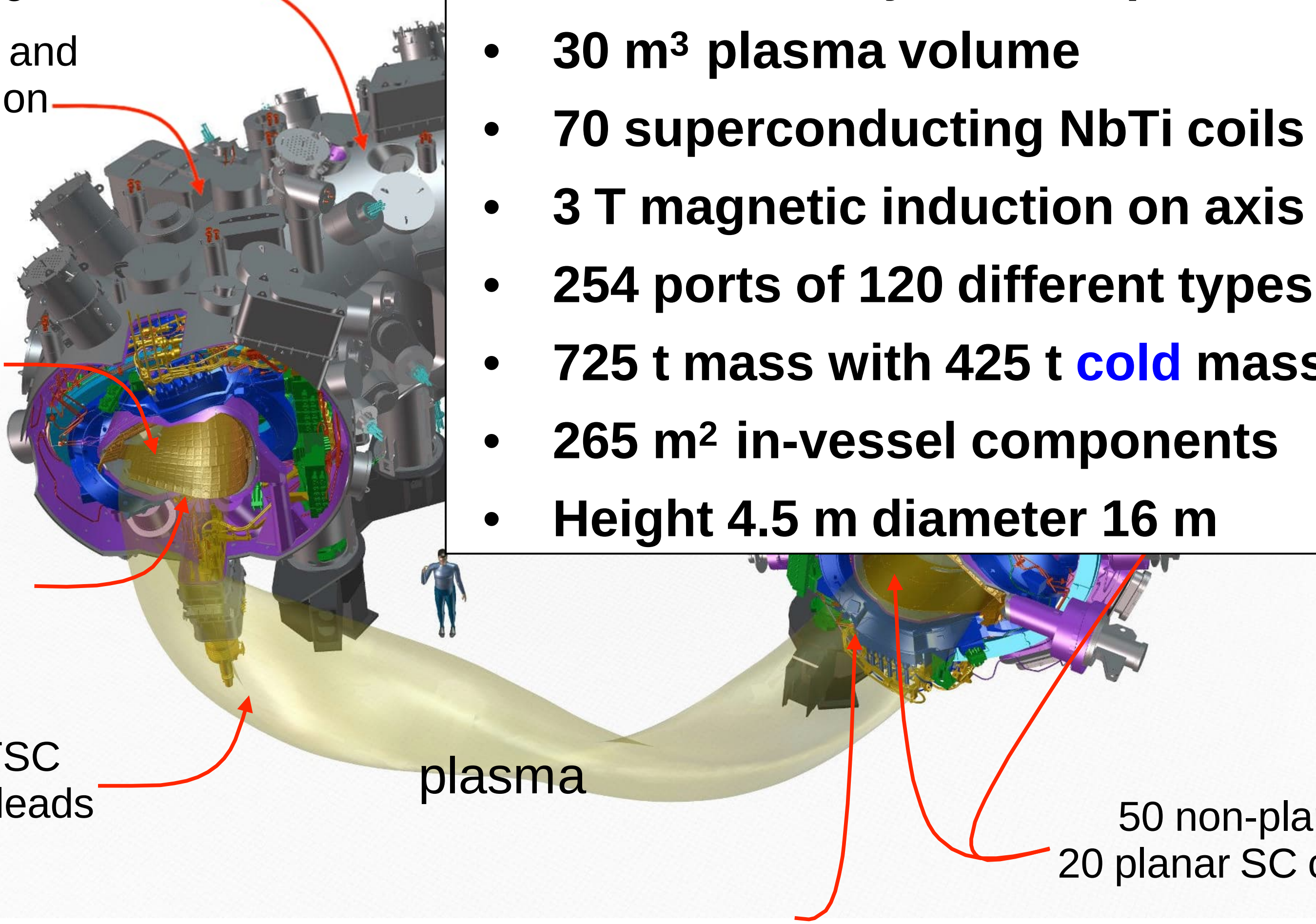
Integration of the coil / vessel system into a cryostat is a significant engineering challenge



Bosch et al., IAEA-FEC 2012

Integration of the coil / vessel system into a cryostat is a significant engineering challenge

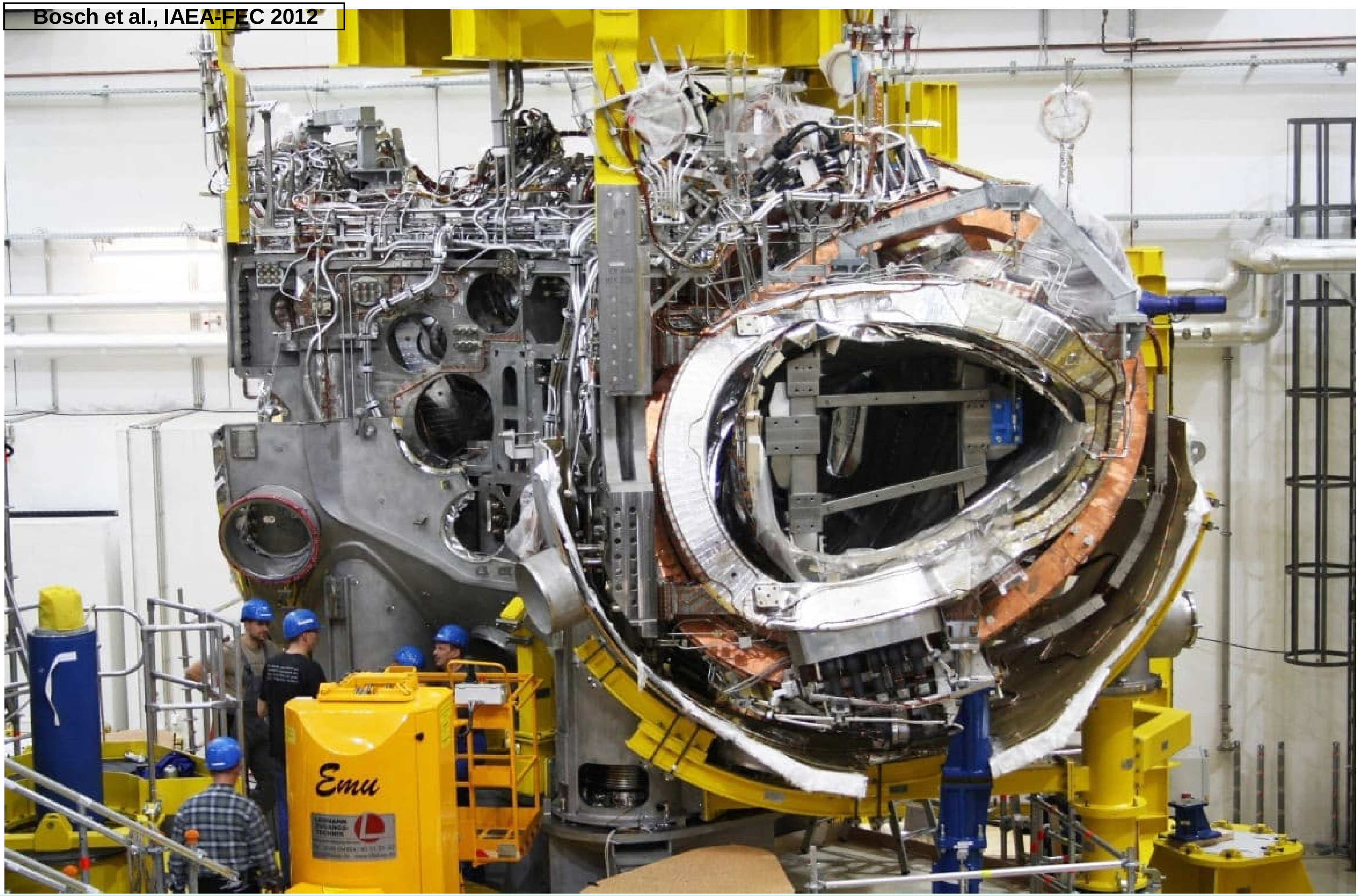
- **5.5/0.53 m major/minor plasma radius**
- **30 m^3 plasma volume**
- **70 superconducting NbTi coils**
- **3 T magnetic induction on axis**
- **254 ports of 120 different types**
- **725 t mass with 425 t cold mass**
- **265 m^2 in-vessel components**
- **Height 4.5 m diameter 16 m**



Bosch et al., IAEA-FEC 2012

First magnetic assembly in cryostat of the W-7X stellarator commenced in October 2009

Bosch et al., IAEA-FEC 2012

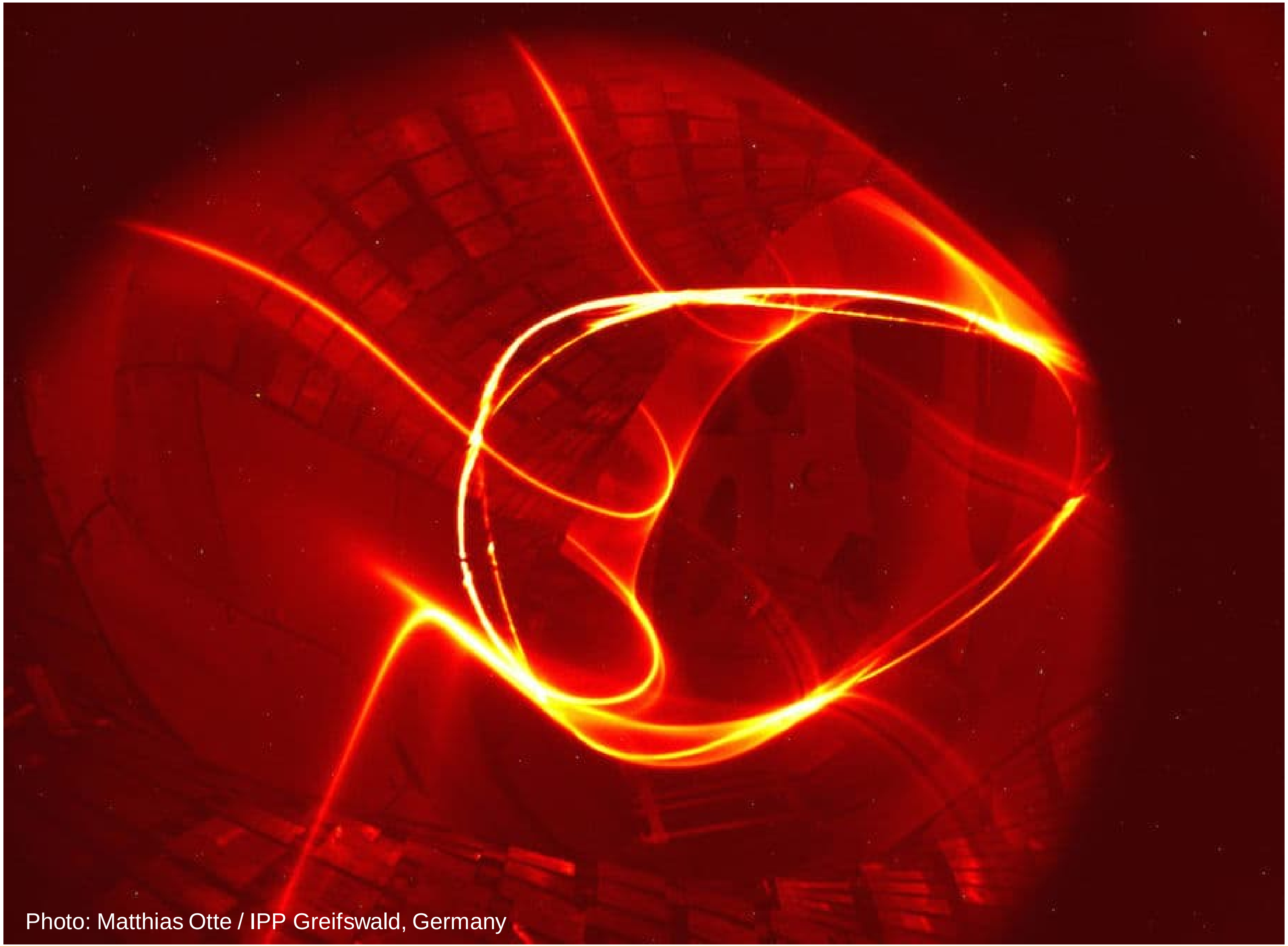


The shape of the vacuum vessel was optimized for the plasma

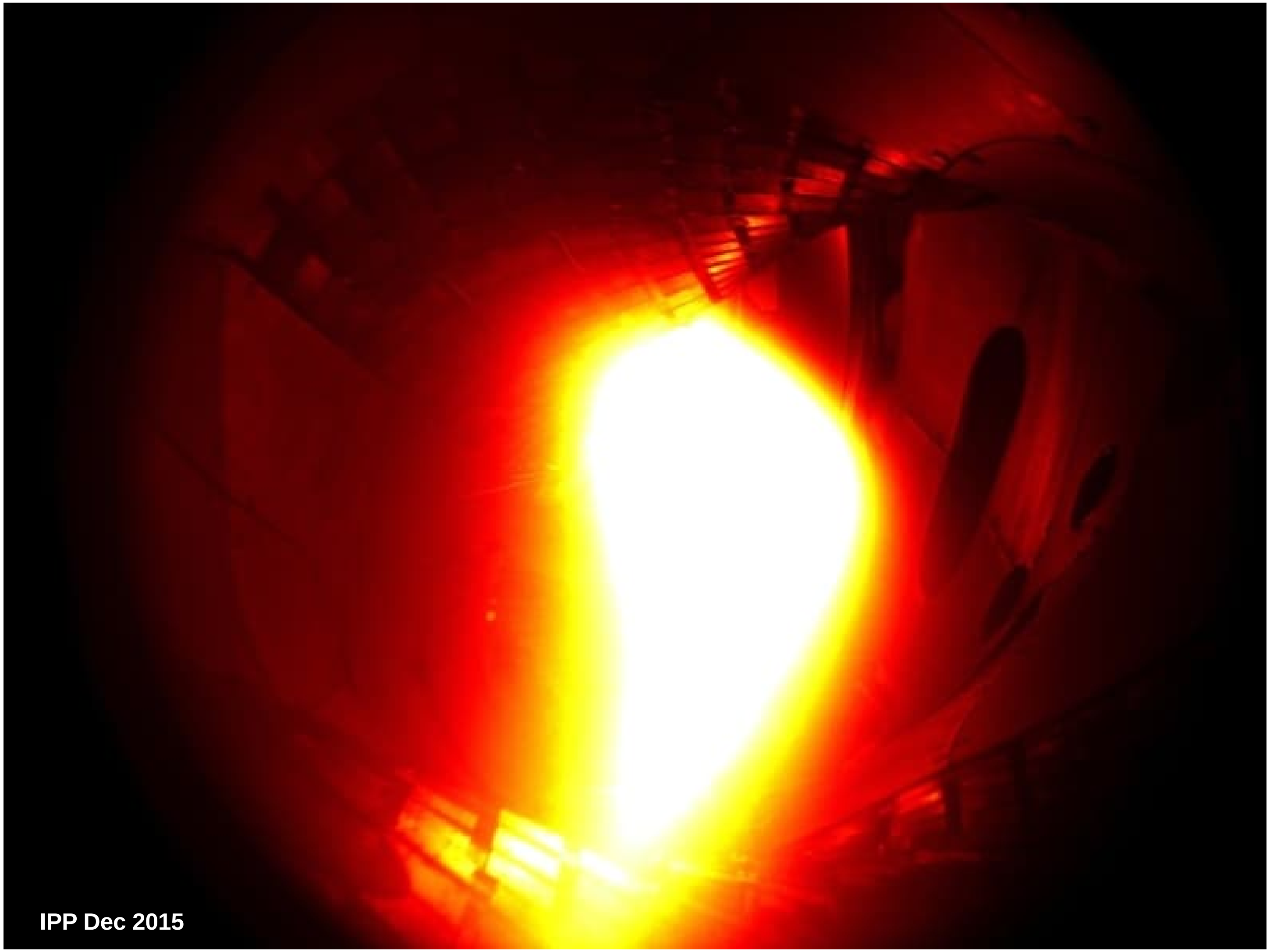
Hartmann et al., IPP 2013

As of August 2013, the cryostat is closed ⇒ work on diagnostics commenced

Field line tracing is performed by injecting electrons into a Argon filled vacuum vessel

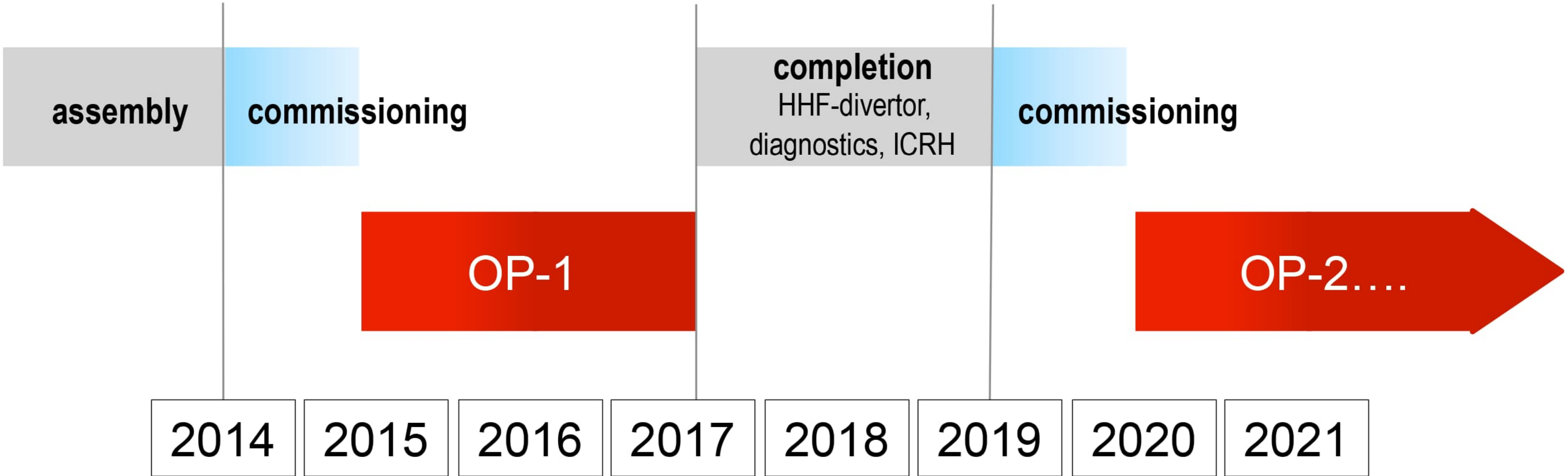


First plasma in W7-X was executed in helium on Dec 10, 2015



Germany's chancellor Angela Merkel initiates W7-X's first hydrogen plasma in Feb 2016

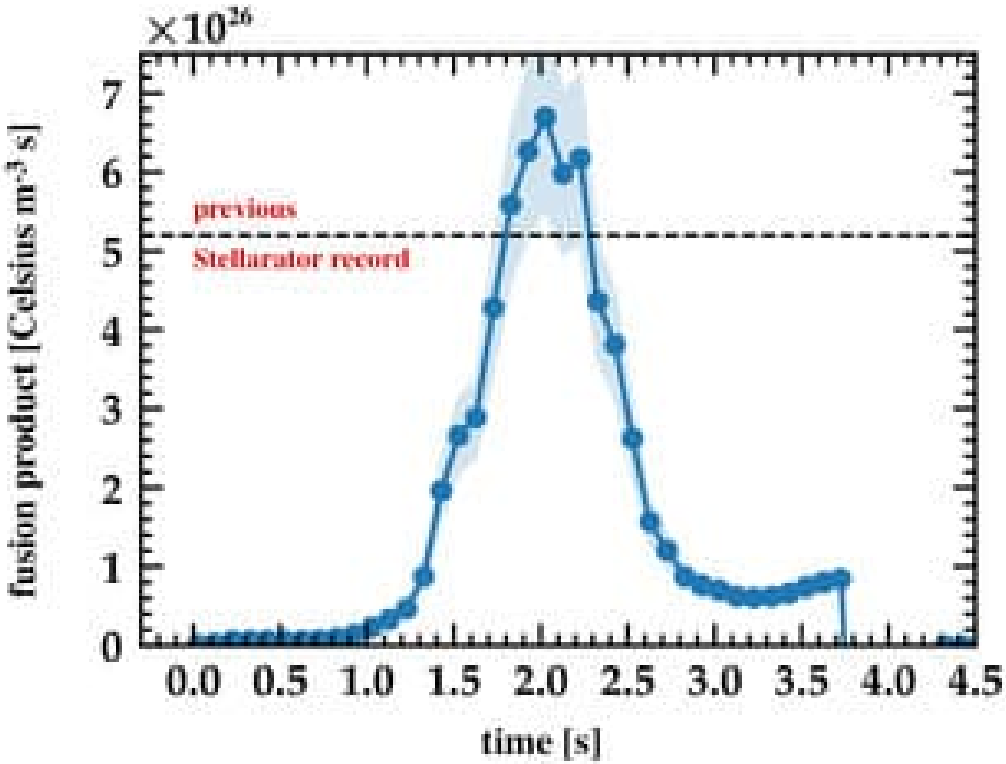
First results from the W-7X stellarator were obtained during OP-1, full performance in ongoing campaign

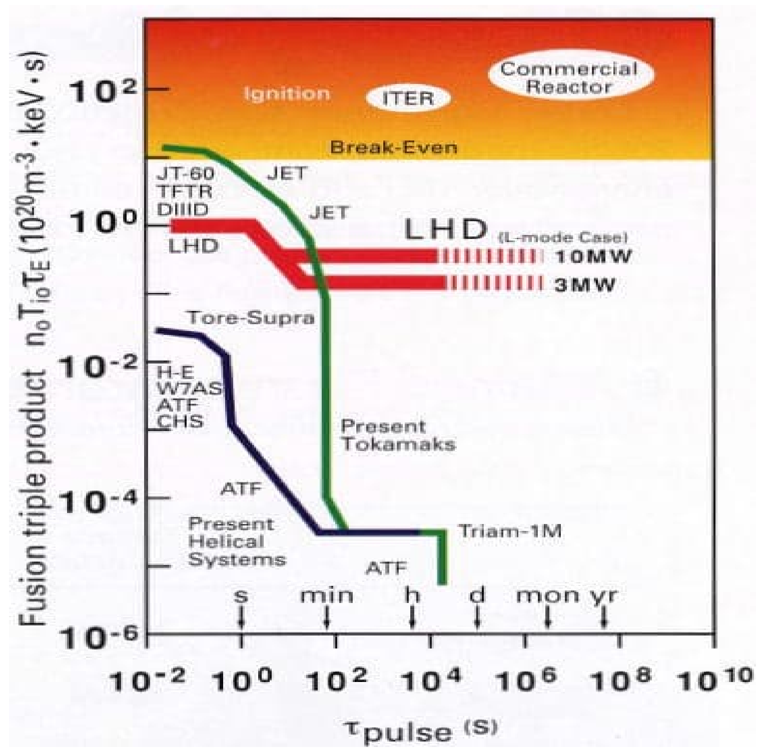


Delayed until 2022-23

- **Operational phase 1: inertially cooled divertor ⇒ 10 s at 10 MW input power, 50 s at 1 MW**
- **Operational phase 2 ongoing (delayed because of corona): installation of high heat flux divertor ⇒ 30 min operation at 10 MW**

New world record in stellarator fusion product in W7-X (press release June 26, 2018)

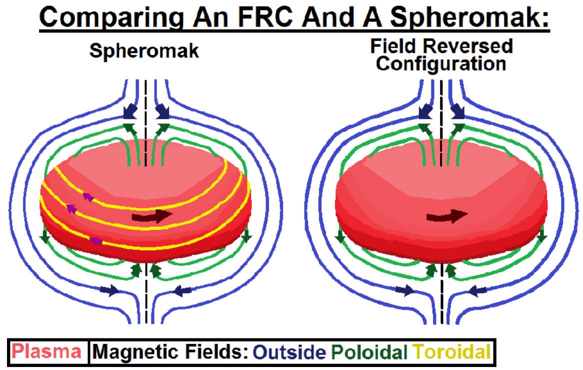


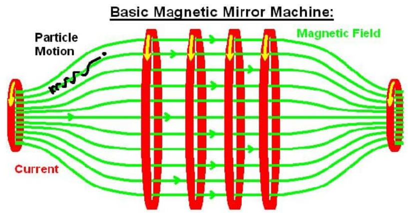


- **Fusion product 6x10^{26} Celsius m^{-3} s ≈ 0.5x10^{20} keV m^{-3} s was obtained with T_i > 3 keV and n_i = 0.8x10^{20} m^{-3}**

Other magnetic confinements concepts include reversed field pinches, spheromaks and mag. mirrors

- Reversed field pinch: $B_T > 0$ in core, $B_T < 0$ in the edge → strong magnetic shear prevents instabilities, but "dynamo effect" limits τ_E
- Spheromaks: large internal electric currents (magnetic fields) to balance MHD forces
- Field reversed configurations: spheromak without internal toroidal field
- Magnetic mirrors: particles reflected at higher B due to conservation of magnetic moments





Inertial confinement fusion

Inertial fusion is tightly coupled to development of high-power lasers

1970 - 1980 | 1980-2008 | 2009-2021 | 2030?

JANUS
100 J IR

ARGUS
1 kJ IR

SHIVA
10 kJ IR

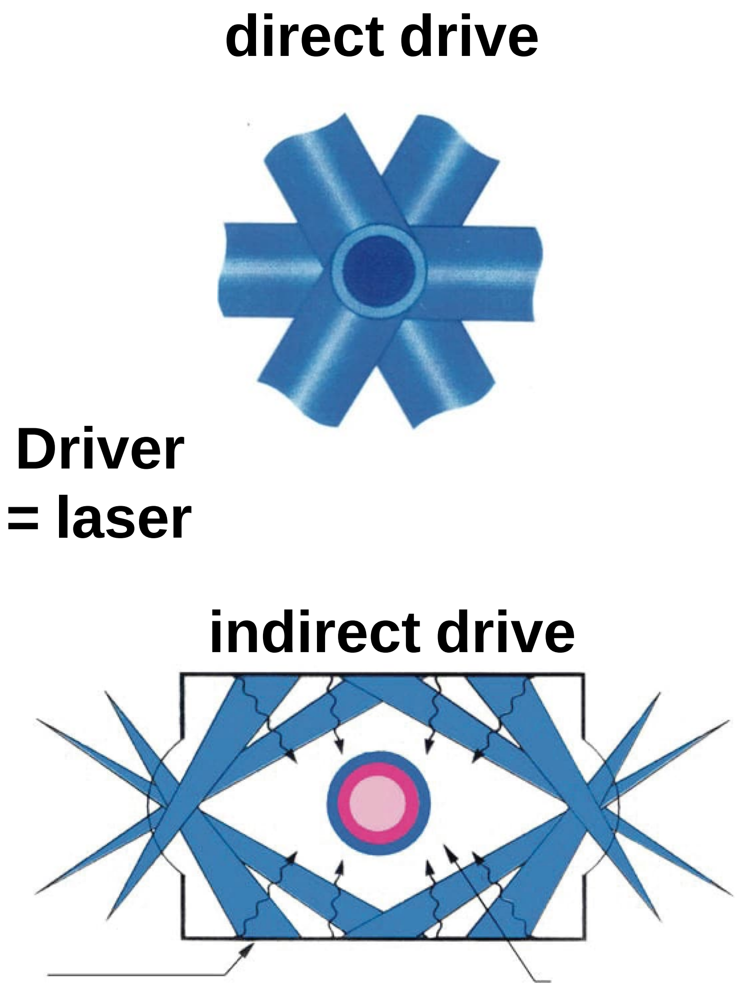
NOVA
30 kJ UV

NIF: 1.8 MJ UV, **500 TW**

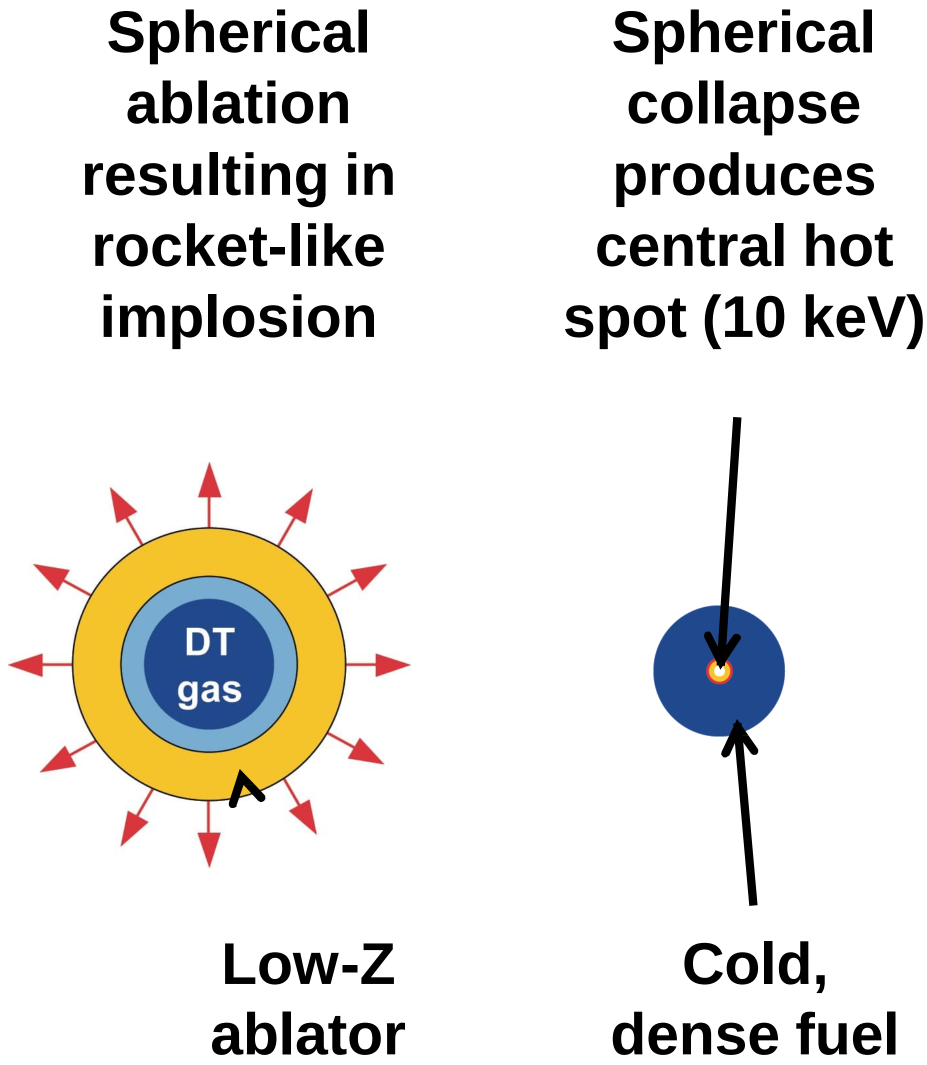
US line of laser development ⇒ fission/fusion hybrids

- **Laser / inertial fusion development also in France and Japan**

The principal approaches to inertial confinement fusion are direct and indirect drive



Lindl et al., IAEA-FEC 2004

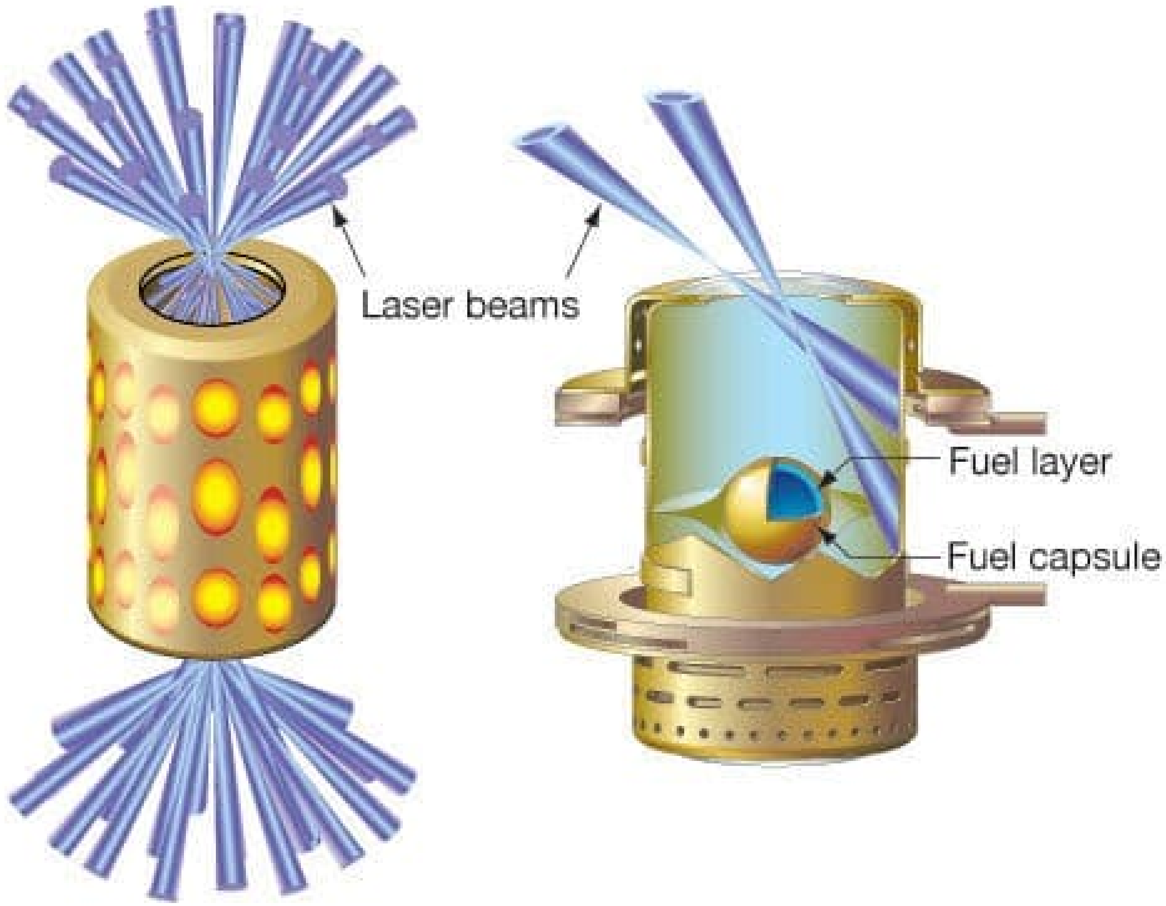


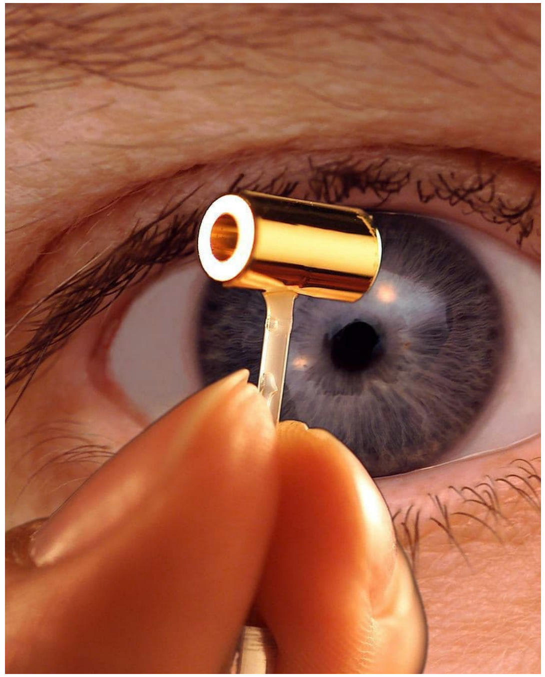
Video: inertial confinement fusion

Video: basic principle of laser fusion

https://www.youtube.com/watch?v=Wg8R1lrAiM4

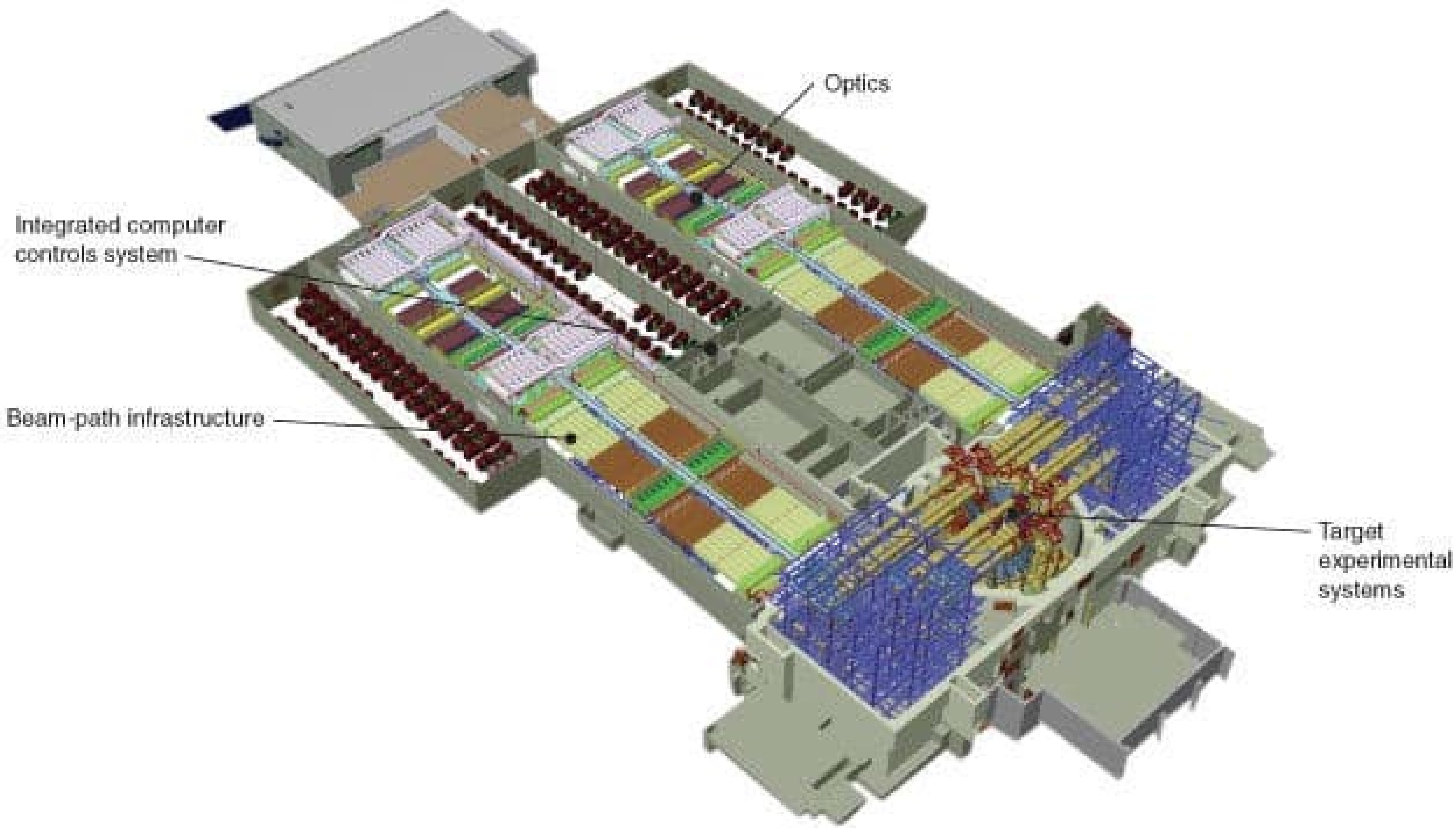
Indirect drive (laser irradiation of a gold hohlraum) is the most promising concept





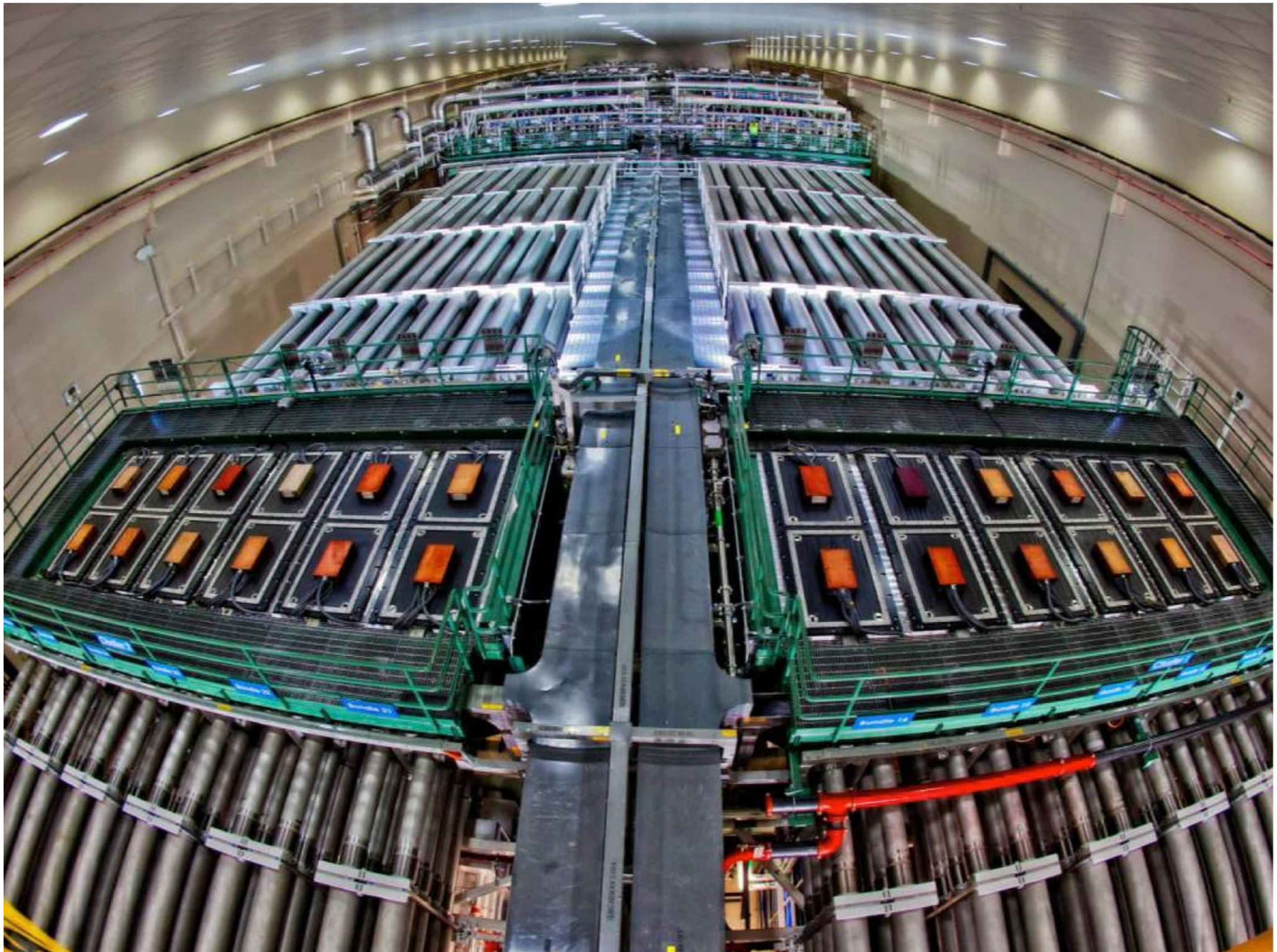
http://lasers.llnl.gov

The National Ignition Facility (NIF) is currently the world’s largest laser facility



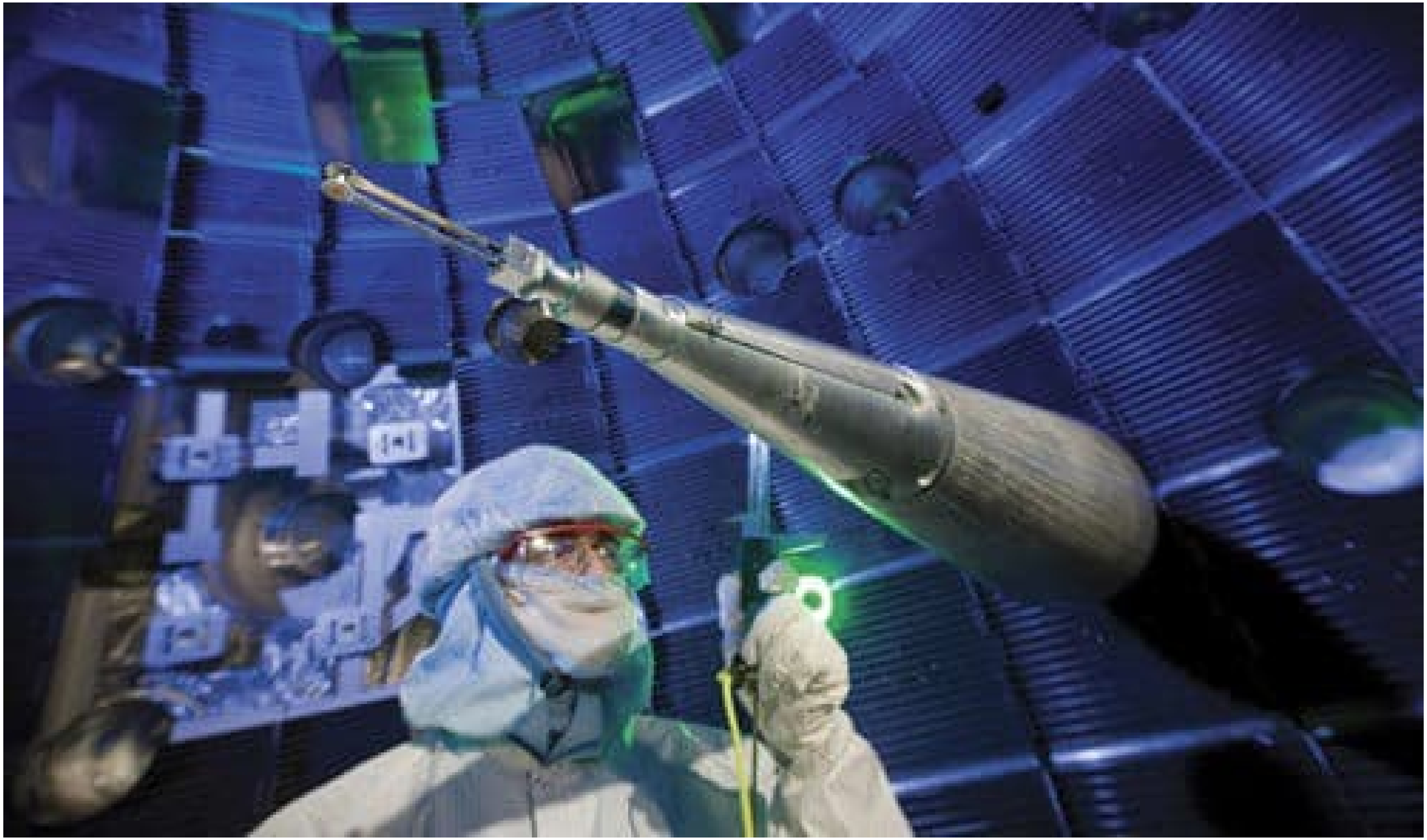
http://lasers.llnl.gov

View of NIF laser bay which corresponds to size of a football stadium



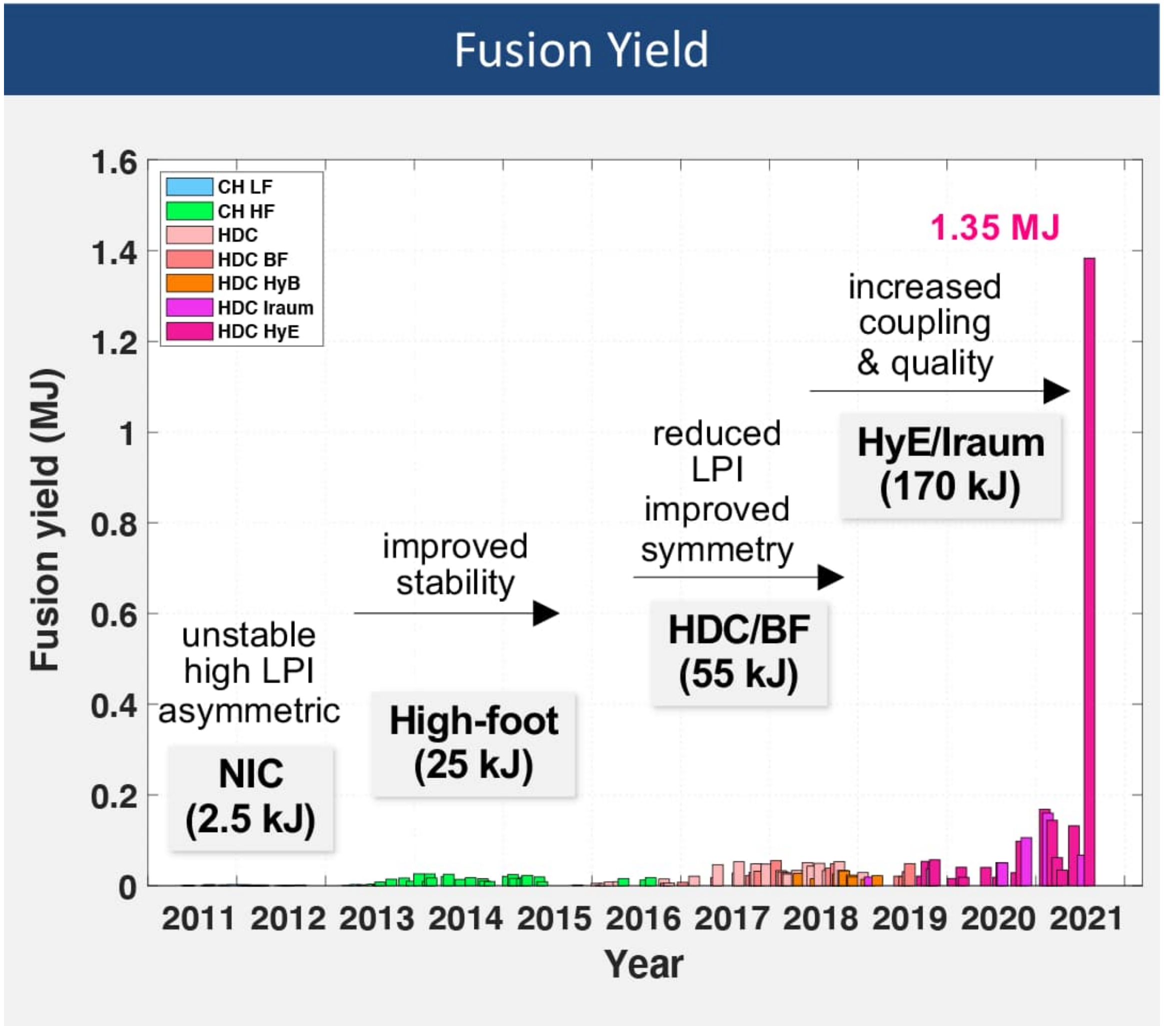
http://lasers.llnl.gov

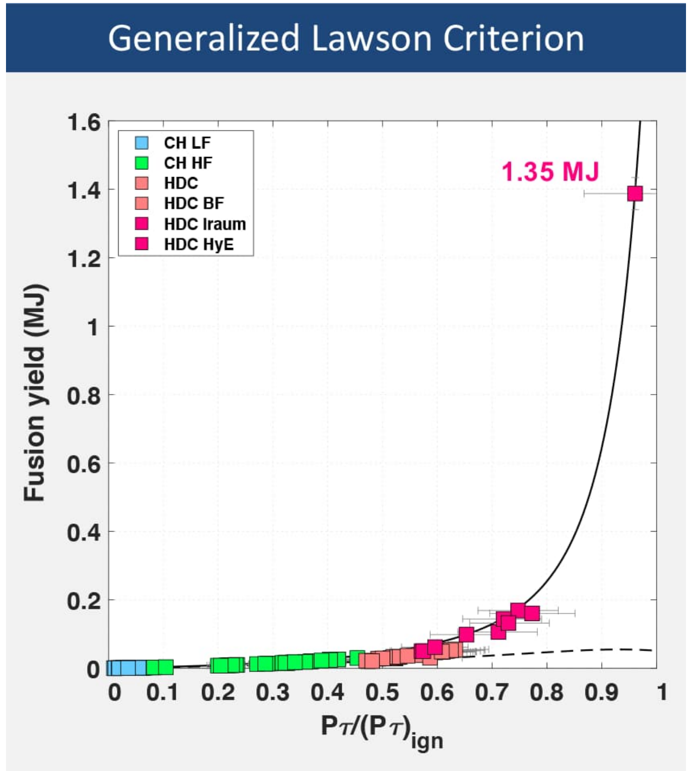
In NIF, laser energy from a 196-beam system is bundled onto a sub-centimeter capsule



http://lasers.llnl.gov

Since 2010, NIF has slowly approached self-heating and ignition, record-breaking 1.35 MJ yield

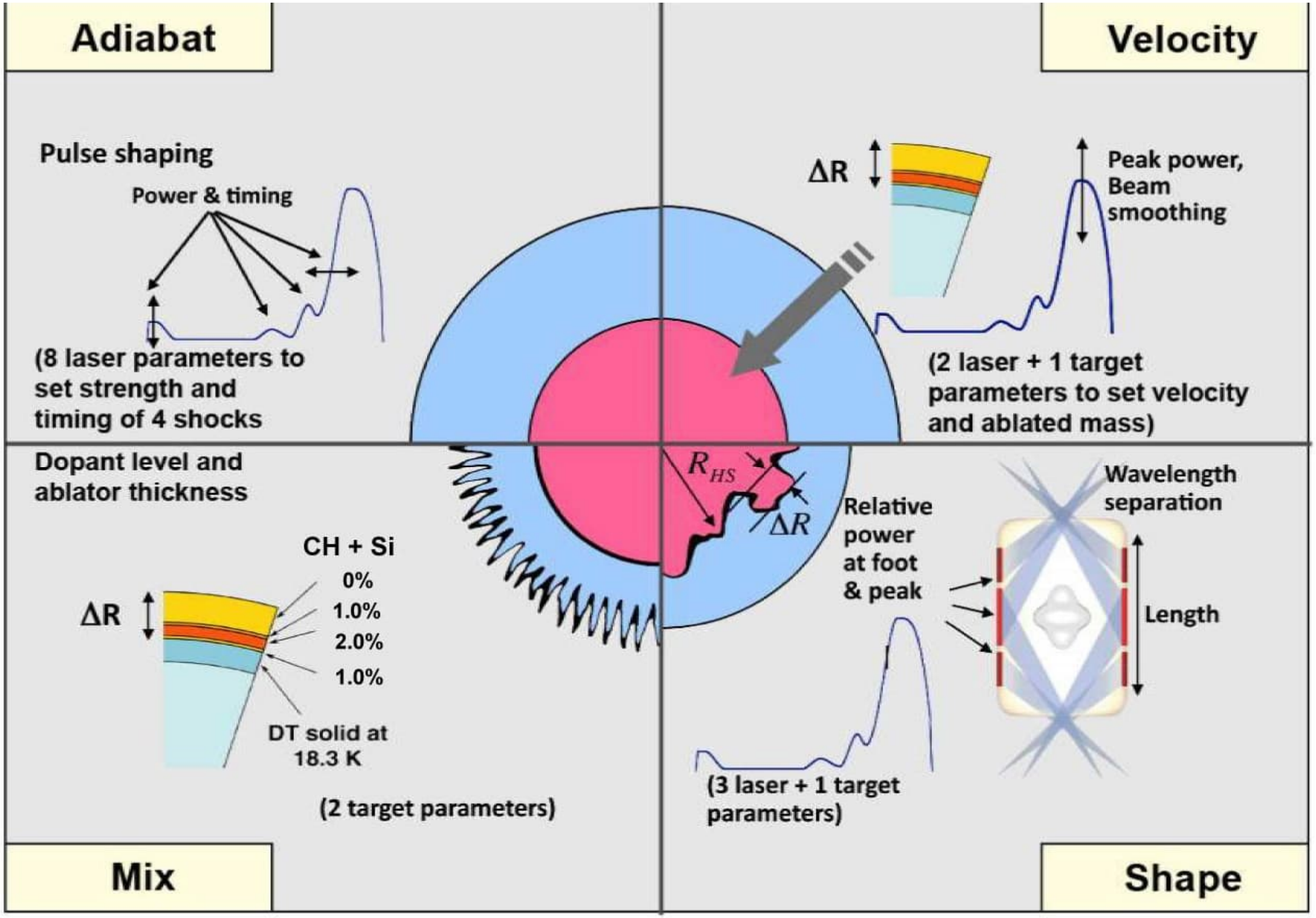




- **Hohlraum is driven by 1.9 MJ laser energy ⇒ target gain of 0.7**

APS-DPP 2021: LLNL

To achieve improved performance, the dopant levels and ablator thicknesses need to be improved



Dunne et al. TOFE 2012

Breakeven in NIF (press release 13.12.2022)

- **For the first time more energy from a fusion reaction than was delivered to the capsule.**
- **The input of 2.05 megajoules (MJ) to the target heated the diamond-shelled, spherical capsule to over 3 million degrees Celsius and yielded 3.15 MJ of fusion energy output.**
- **This is scientific break-even which has never been achieved before in fusion devices (not even in tokamaks)**
- **More details of this in ICF lecture later in this course**

Presemo quiz #2

https://presemo.aalto.fi/fet/

Summary

- **The three main fusion plant concepts include tokamaks, stellarators, and laser fusion devices**
  - Fusion conditions close to break-even have been achieved in tokamaks (with carbon plasma-facing components) and indirect-drive laser devices
- **Long-term plans for developing tokamaks into power plants are ITER and DEMO, more aggressive SPARC**
  - Laser fusion ⇒ pure-fusion or fission-fusion hybrid
  - Stellarator concept awaiting assessment in next-step devices
- **Fusion performance currently limited by physics (instabilities, transport) ⇒ materials, technology (coils, laser system, steady-state and burn control)**