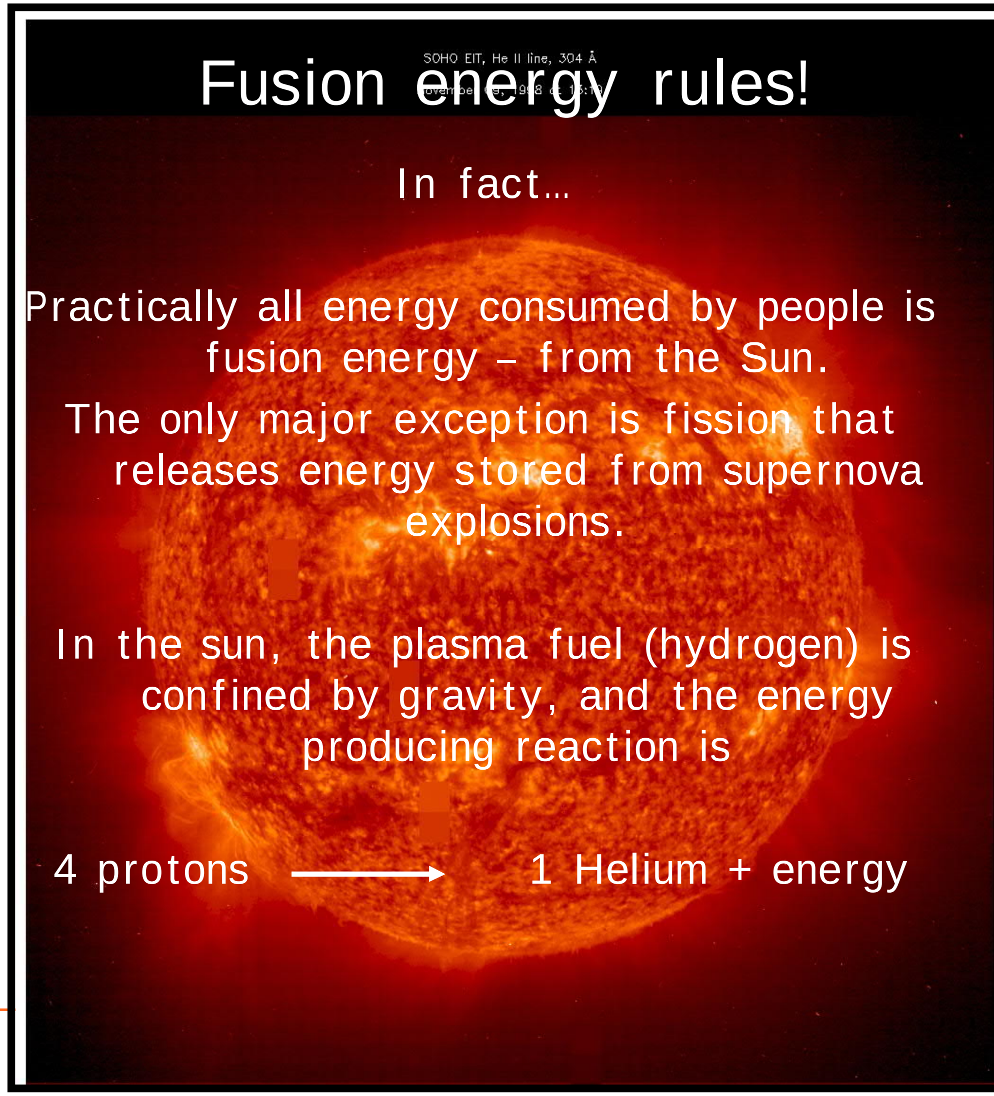
Aalto University
School of Science

Lecture 11:
Earthly plasmas -- fusion

Today’s menu

- Fusion as energy producing mechanism
- Concept of energy density
- Lawson criterion
- Limiting a plasma: limiters, divertors and the SOL
- Heating a plasma: neutral beams, ECRH & ICRH
- Diagnosing plasma
- Stellarator
- ICF
- ITER & DEMO(s)


Fusion energy rules!
SOHO EIT, He II line, 304 Å
In fact…
Practically all energy consumed by people is fusion energy – from the Sun.
The only major exception is fission that releases energy stored from supernova explosions.
In the sun, the plasma fuel (hydrogen) is confined by gravity, and the energy producing reaction is
4 protons → 1 Helium + energy

So why not produce fusion energy on Earth?

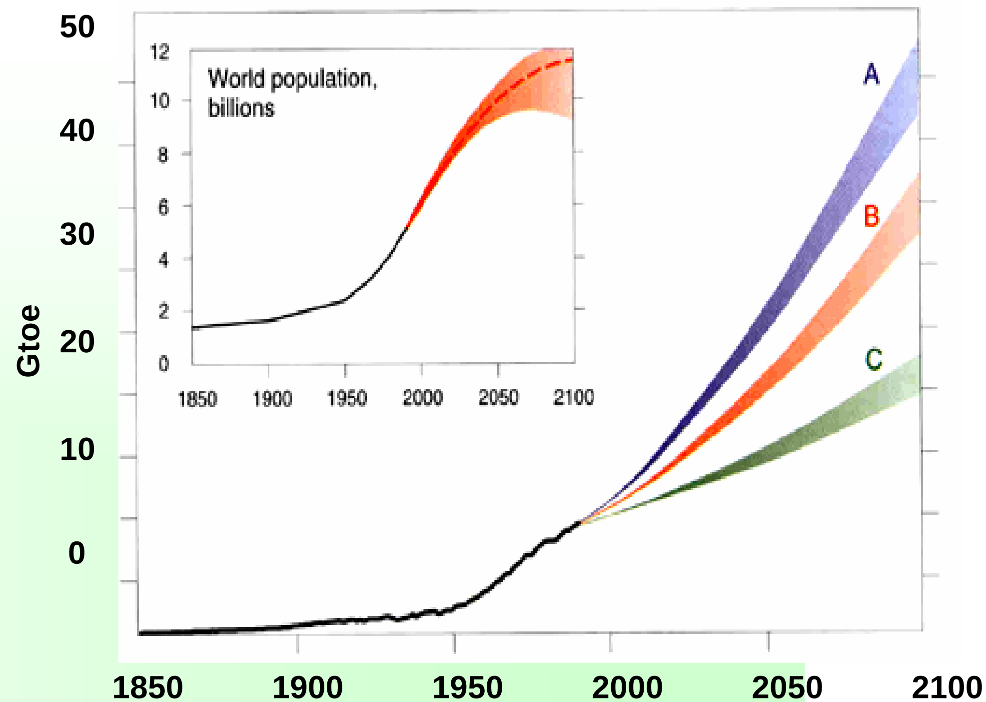
Would be badly needed ...

Energy forecast until 2050

- **Population doubles**
- **Energy consumption get 2-3 folded**
- **Problems with easy fossil sources**
- **Additional capacity needed min 10 - 20 TW**

Potential candidates for Additional capacity:

- **renewables (H2O, bio, solar, wind)**
- **fission (^{238}U, Th)**
- **fusion**

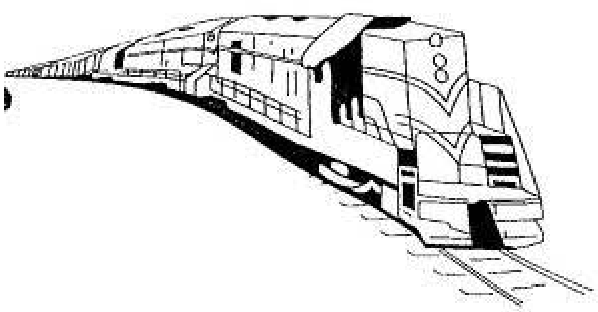


Energy density:
Fuel needed by a 1000 MWe power plant per year

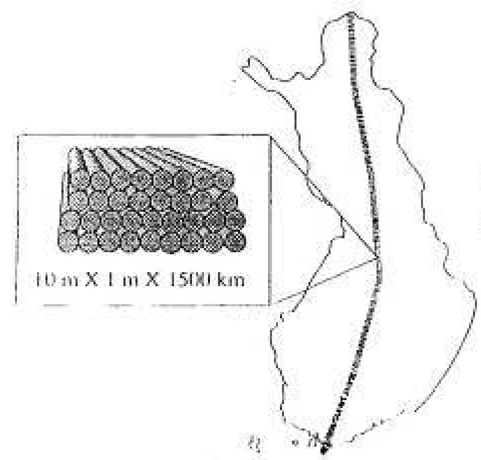
Nuclear power plant
30 tons of enriched Uranium
(two truck loads)

Fusion power plant
300kg D + Li

eV vs MeV



Coal fired power plant
2 400 000 tons coal
(35 000 cargo vans)



Wood burning plant
15 000 000 m^3 logs

How about not using fuel at all?

- **80 km^2 solar panels,**

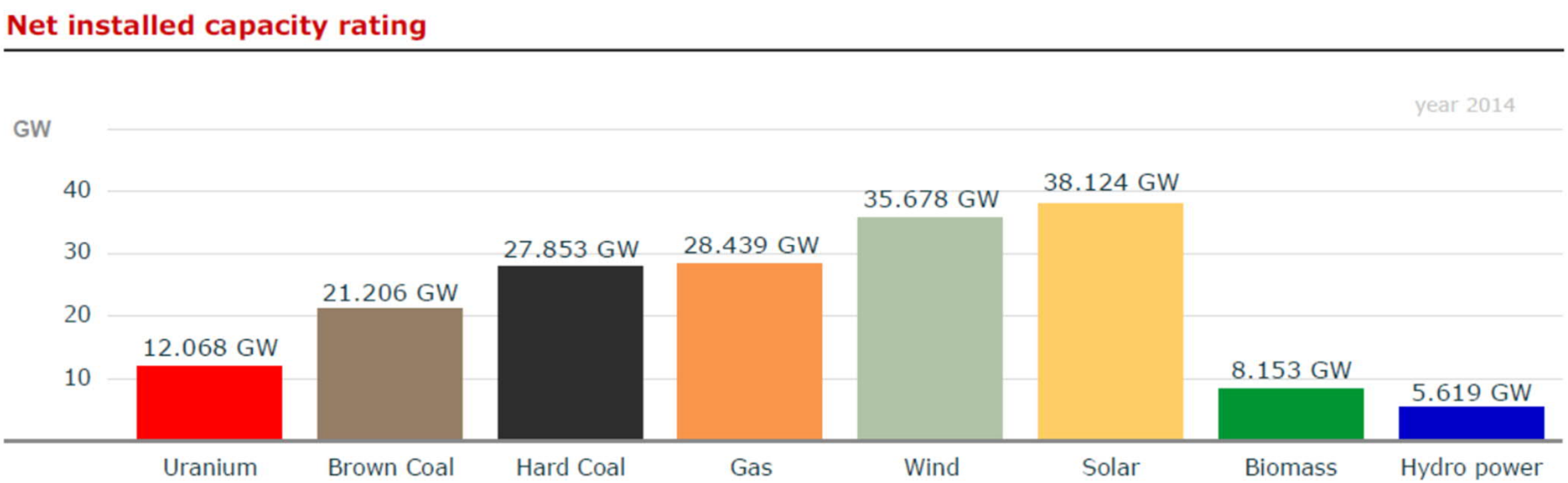
or

- **1000 MWe wind mills**

+ back-up power production ...

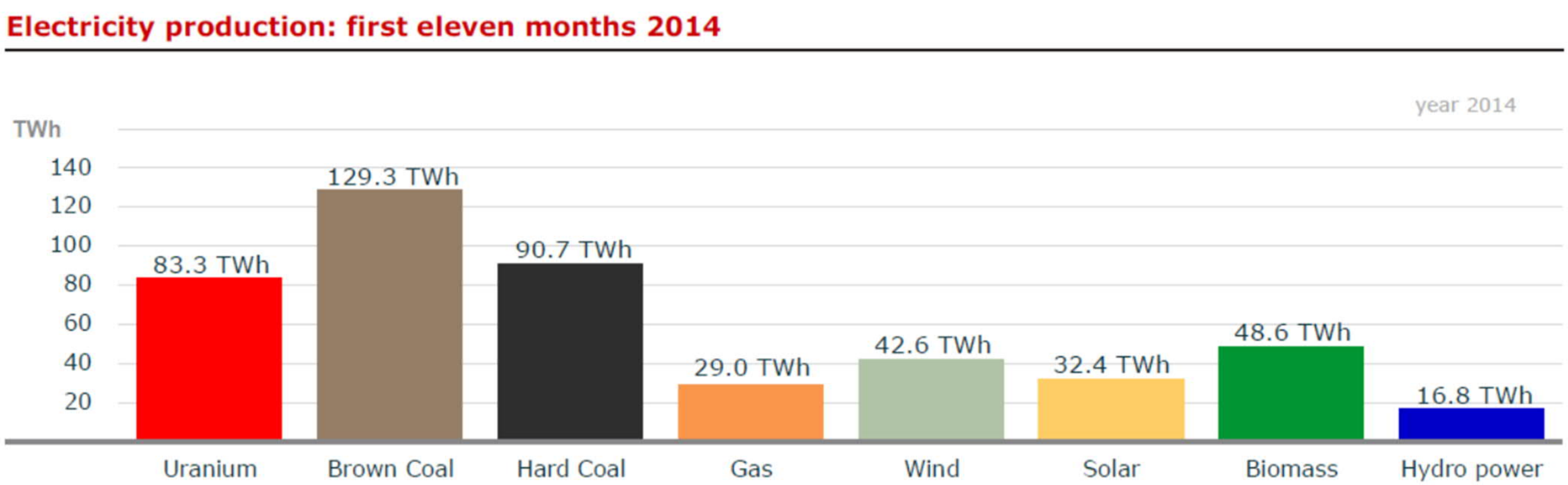
Capacity vs reality: case Energiewende

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE
Electricity production from solar and wind in Germany in 2014

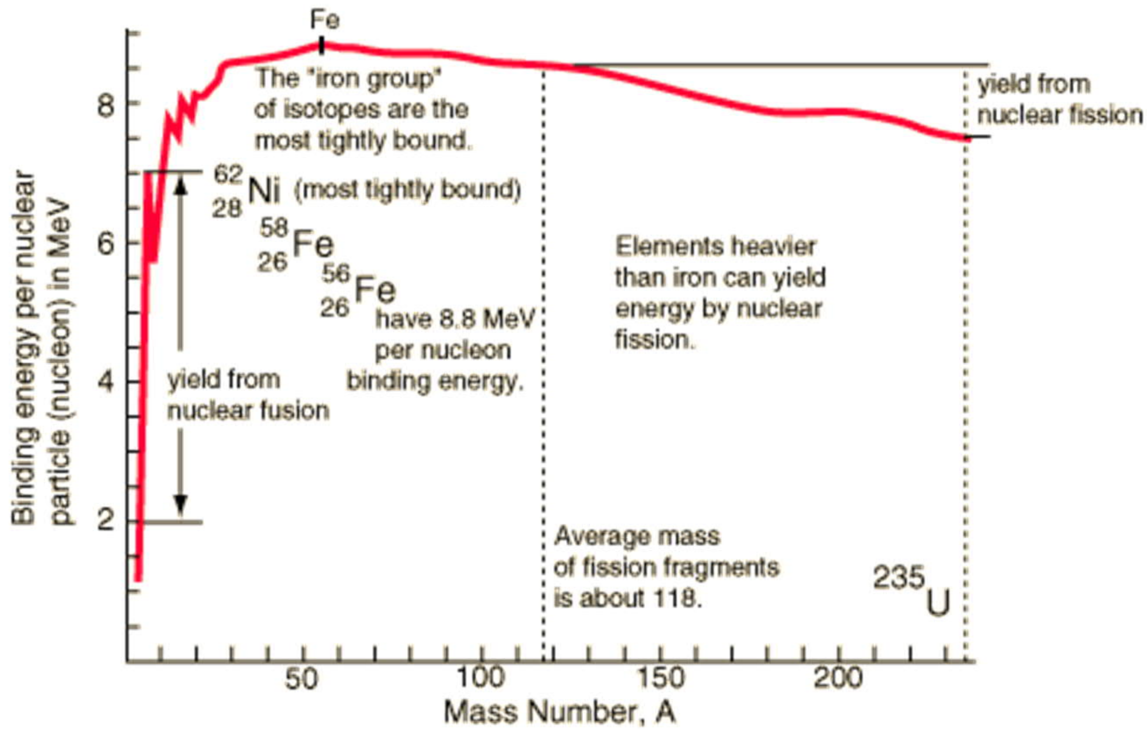


Capacity vs reality: case Energiewende

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE
Electricity production from solar and wind in Germany in 2014



From the energy gain point-of-view, fusion is *very* attractive…



Additional benefits

- safe (read: hard to achieve…)
- Environmentally benign (no pollution)
- no greenhouse gases ➔ fights climate change
- ash from nuclear burn = precious He ➔ not radioactive
- does not produce materials for proliferation
- fuel sources practically limitless:

  Deuterium and Lithium ($\rightarrow$ Tritium: n + Li → He + T)
- Fuel sources ‘democratically’ distributed:
  - sea water ➔ D
  - earth crust ➔ Li

Measuring plasma performance:

Consider the power balance in a fusion reactor:

$P_{out} = P_{fus} + P_{loss}$

$P_{loss} = P_{br} + W_{th}/\tau_E$

Need to maintain fusion conditions

➔ self-produced heating power > losses:

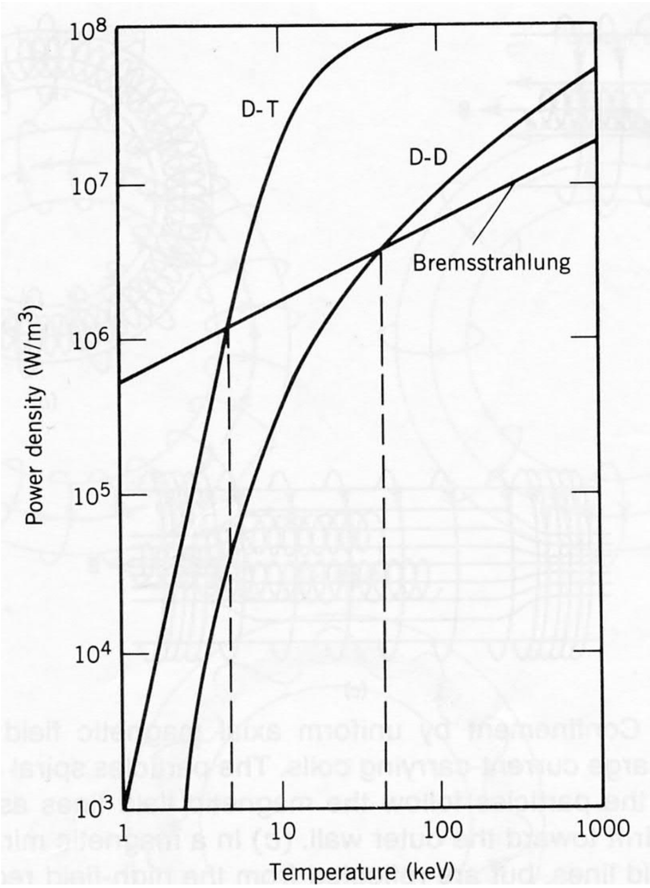
$P_{in} = \eta P_{out} > P_{loss}$; η = conversion efficiency

$\eta(P_{fus} + P_{loss}) > P_{loss}$

➔ $\eta P_{fus} > (1- \eta)P_{loss}$

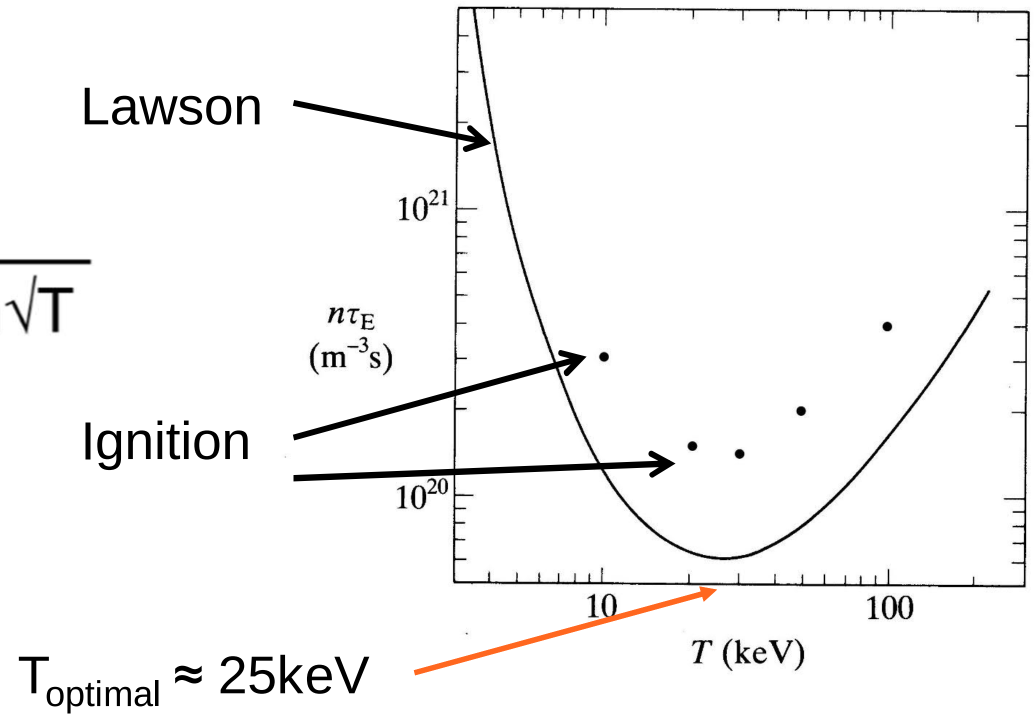
Fighting for dominance

- $P_{br} = \alpha_{br} n^2 \sqrt{T}$
- $W_{th} = 3nT$; $(W_e + W_i)$
- $P_{fus} = (n^2/4)\langle\sigma v\rangle Q_{fus}$



➔ Lawson criterion

$$n\tau_E > \frac{3T}{\left(\frac{\eta}{1-\eta}\right))\langle\sigma v\rangle\left(\frac{Q}{4}\right)-\alpha_{br} n\sqrt{T}}$$



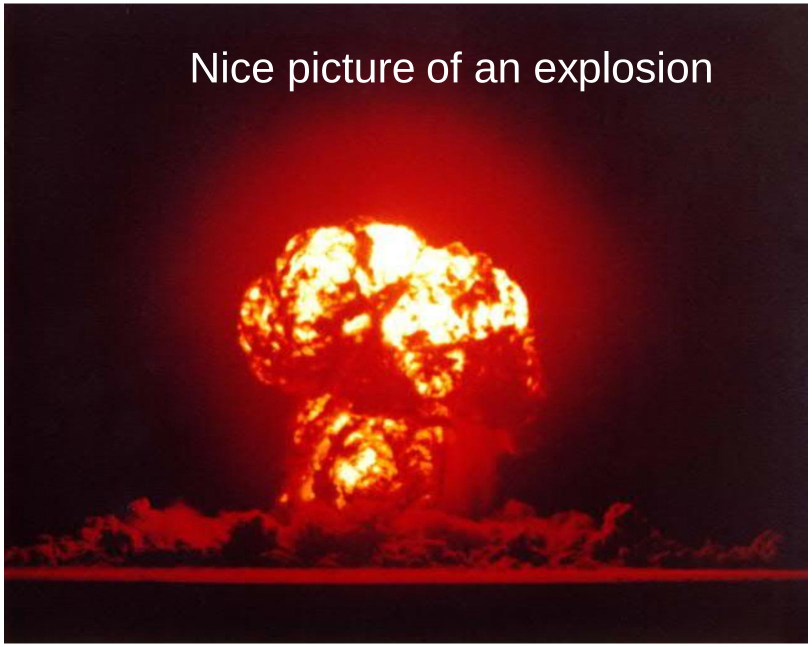
Reaching the criteria, Part I: ICF

Maximize the pressure, nT

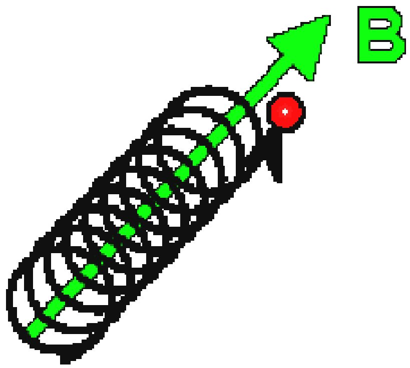
➔ 'inertial confinement fusion' = confinement only by inertia of particles

- First successful(?) experiment already in 1952:
  - Teller-Ulam H-bomb (ignited by a fission bomb
  - Proof of principle for *inertial confinement fusion*

- More constructive use of ICF has been developed over the past 30y or so ➔ NIF at LLNL, USA



Reaching the criteria, Part II: MCF = **Maximize τ**



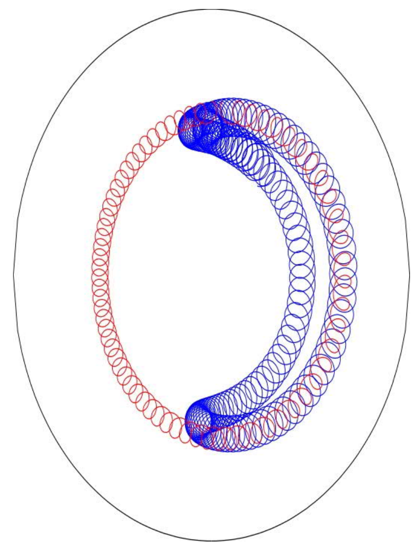
Charged particles glued to magnetic field lines !

… unless the field is inhomogeneous and/or lines are curved

Different geometries

- ★ Magnetic mirrors (1st attempt)
- ★ Stellarator
- ★ Z-pinch,
- ★ θ-pinch,
- ★ reversed field pinch
- ★ … and…

The tokamak



Tokamak Basics

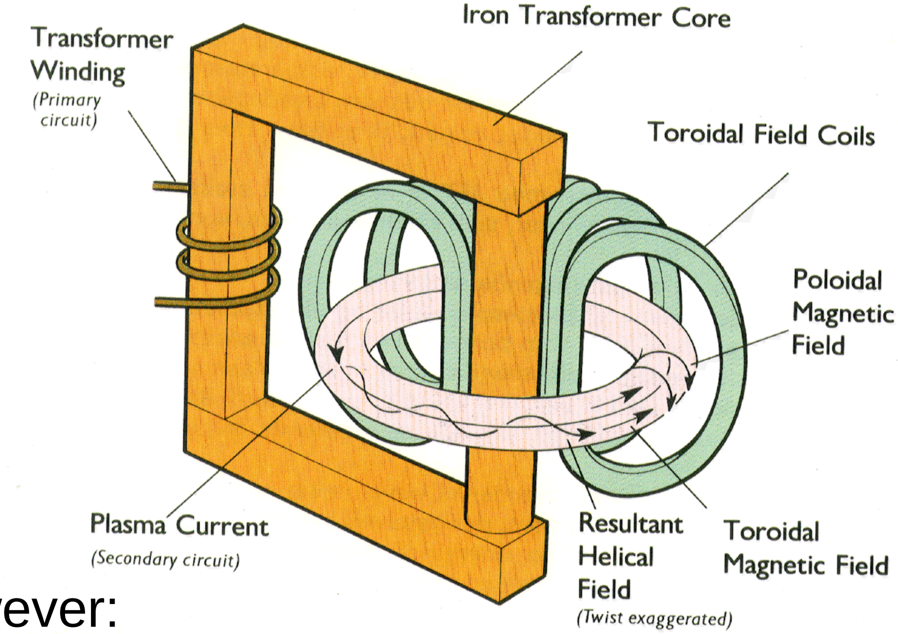
toroidal'naya kamera v magnitnykh katushkakh — toroidal chamber in magnetic coils

Tokamak, the Human Reactor

Plasma confinement:

- *poloidal* field (by plasma current)
- stronger (x10) *toroidal* field (by external coils)

➡ *Helical* magnetic field lines



Based on transformer principle

➡ Suits poorly continuous use… However:
various means of external current drive can facilitate continuous use

Who actually confines what? -- duality in plasma physics

Tokamak confinement from *single particle* point-of-view:

- Charged particles gyrate around toroidal fieldlines = are confined
- Introduce toroidicity
  - ➔ ∇B-drift
  - ➔ $\mathbf{E}_z$
  - ➔ **ExB**-drift in R-direction

➔ Need to short-circuit:

- Introduce $\mathbf{B}_{pol}$

Tokamak confinement from *fluid* point-of-view:

- Force balance:

$$\nabla p = \mathbf{j} \mathrm{x} \mathbf{B}$$

- Tokamak based on induced current $\mathbf{j}_{tor}$

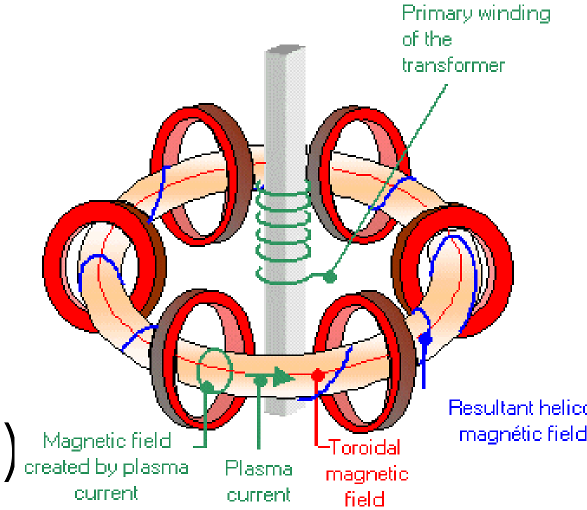
➔ Confining field = $\mathbf{B}_{pol}$ **!!**

$\mathbf{B}_{tor}$ needed to *stabilize* the toroidal plasma ...

In both cases the end result is helical field lines

How is a fusion plasma created?

Marching order



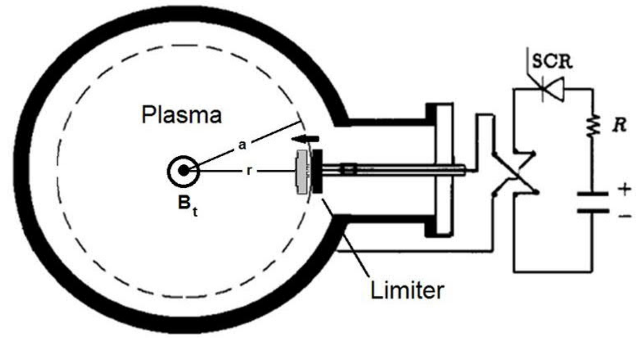
- First of all: start the TF coils ➔ B_T
- Puff hydrogen gas to the chamber: 10^{-5}Pa
- Start ramping current in the primary winding, $I(t)$
  ➔ $B_z(t)$
  ➔ Faraday's law: $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ ➔ E_{loop}
- The toroidal electric field E_{loop}
  – Causes plasma *break-down* = from gas to plasma
  – Drives the plasma current I_p ➔ B_p

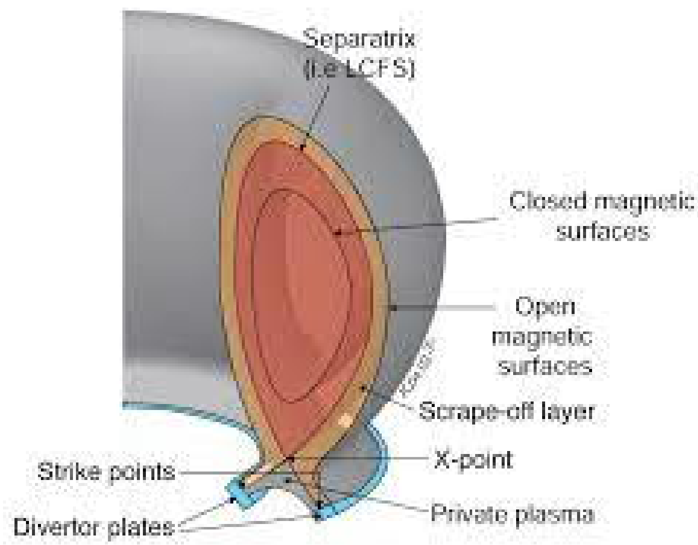
➔ helical field lines & plasma -- and we are ready to go!

How to limit a plasma?

- Limiter geometry (old)
  - Lot's of impurities
  - Difficult to access *H-mode*

- Divertor geometry
  - Create an *X-point*
  - Closed and open flux surfaces
  - Trash bin far from the main plasma
  - Difficult to make stay in *L-mode*…
  - Today's devices





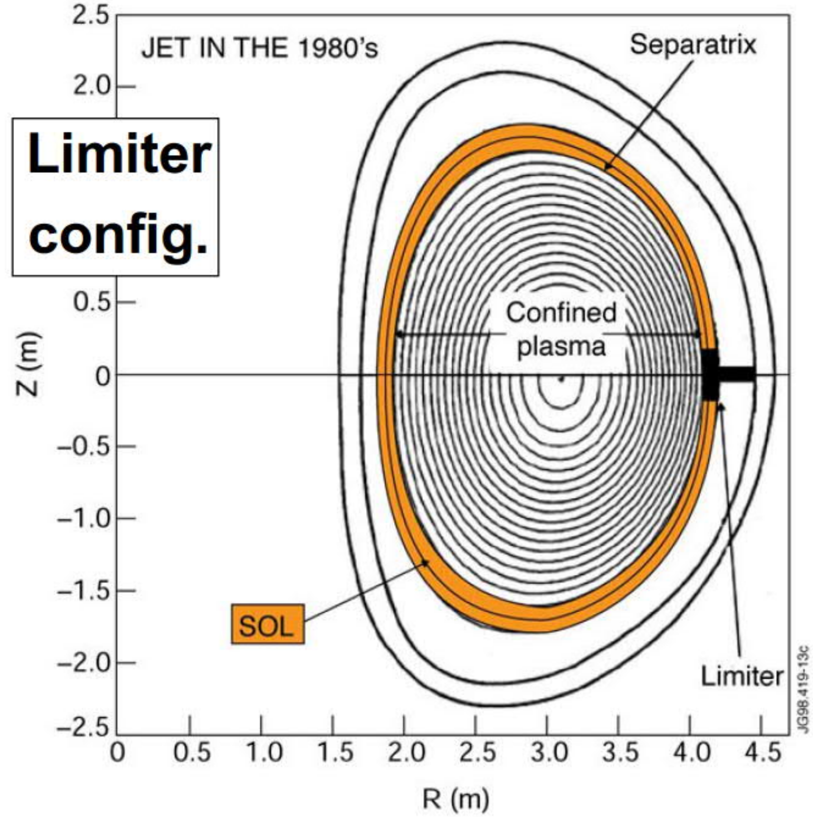
Example: JET tokamak before …

Notice: plasma cross section is not circular

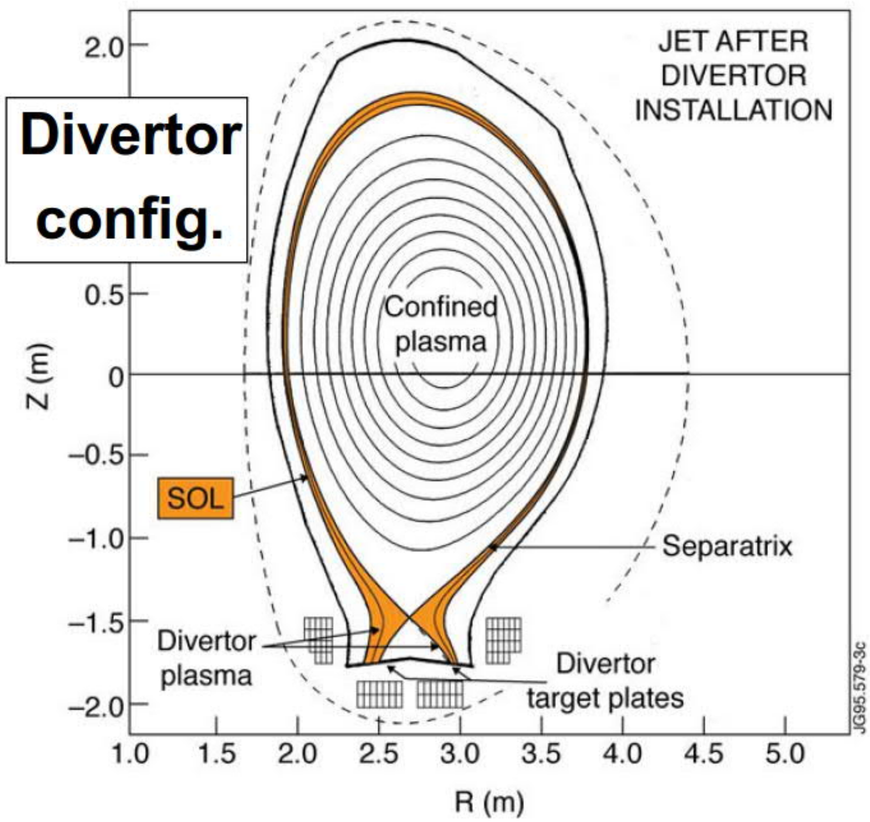
Why does it make sense to elongate vertically?

Nowadays plasmas are *triangular*

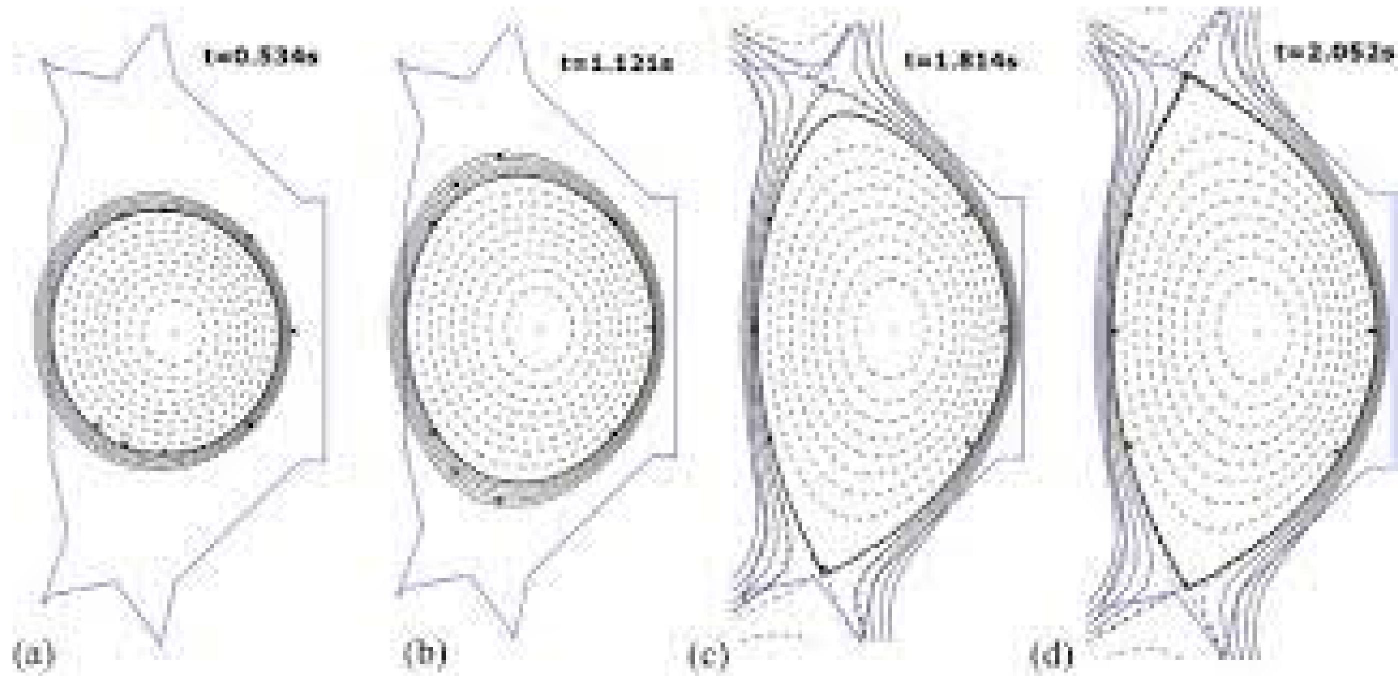
New concept:
Scrape-off layer, SOL



Example: JET tokamak before and now

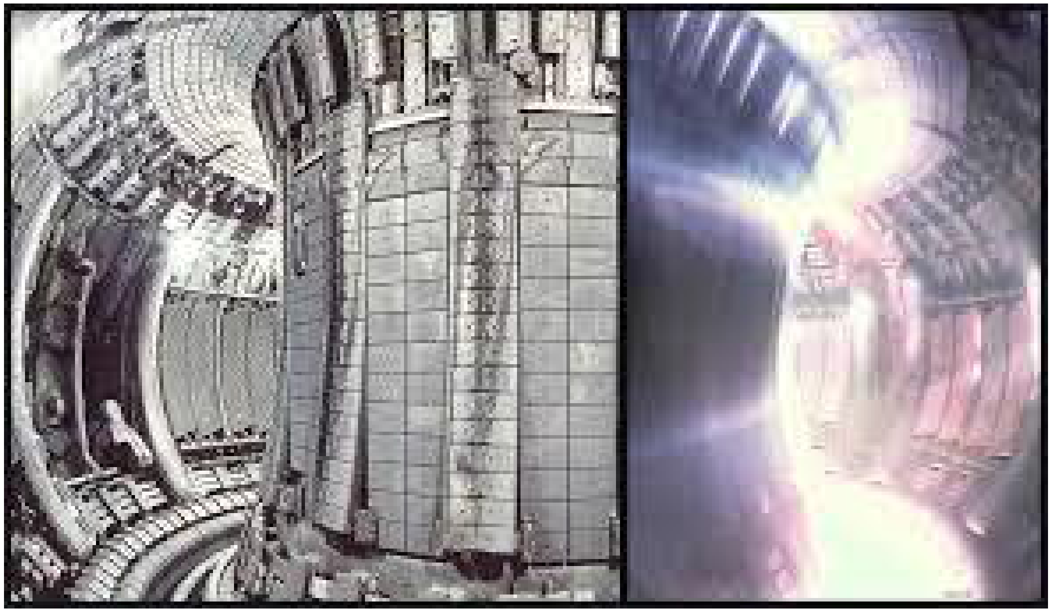


Plasma still starts up at the limiter

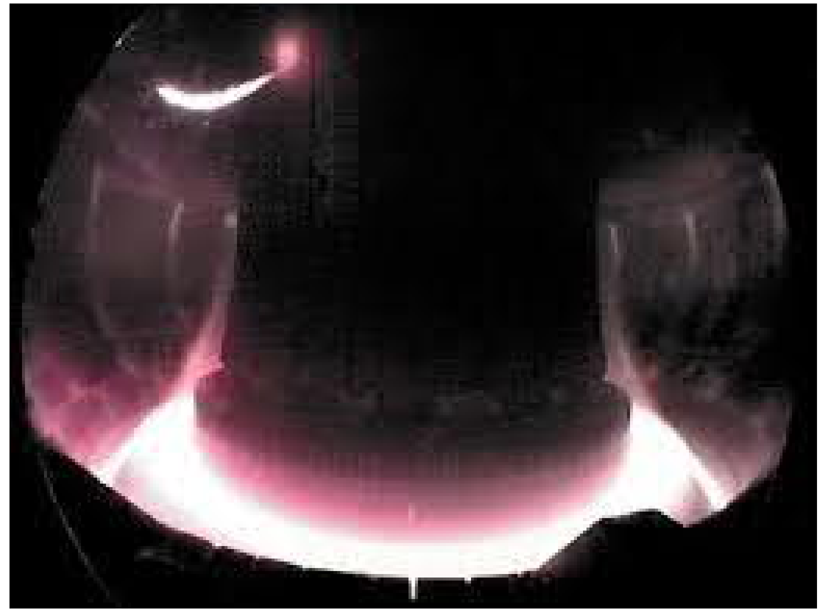


Q.P. Yuan et al., *Plasma current, position and shape feedback control on EAST*
Nuclear Fusion, Volume 53, Number 4

How does a tokamak plasma look like?



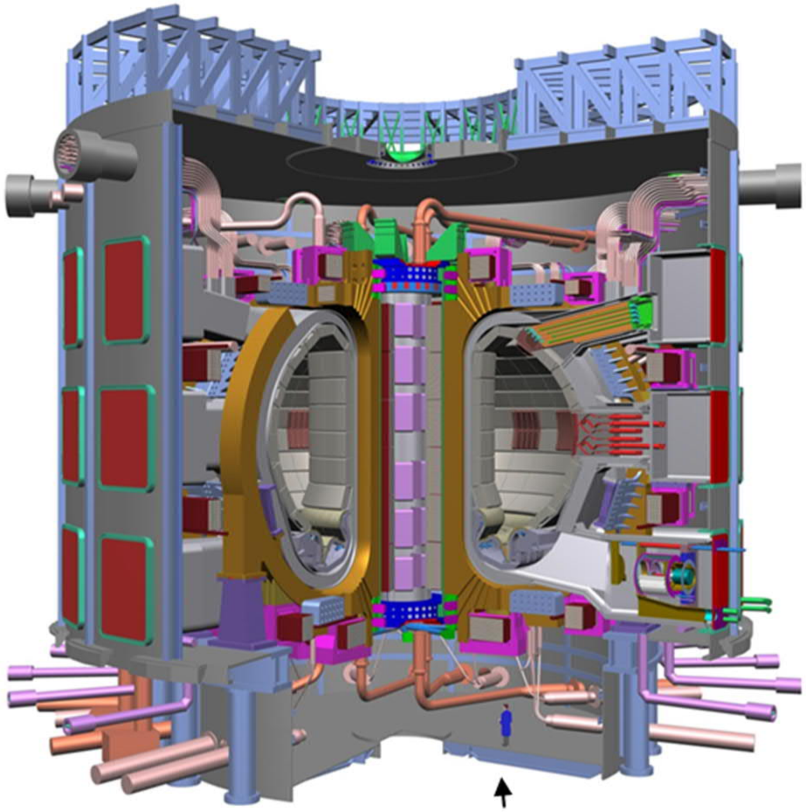
JET tokamak
CCFE
Abingdon, U.K.



ASDEX Upgrade
Max Planck institute
Garching, Germany

How is a plasma heated?

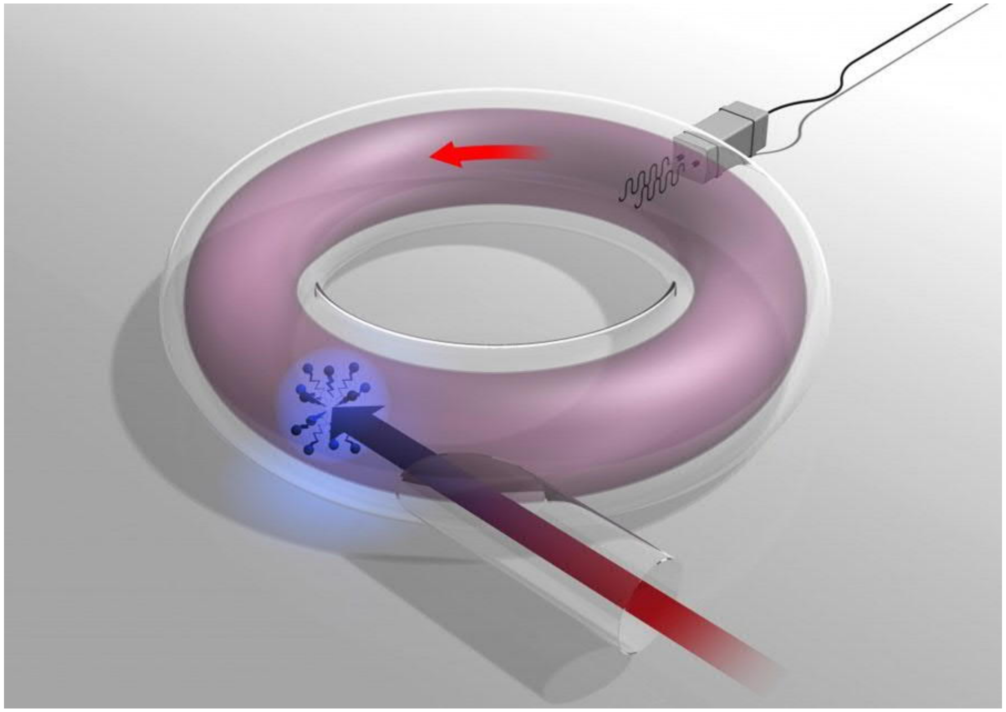
ITER – world's first fusion reactor



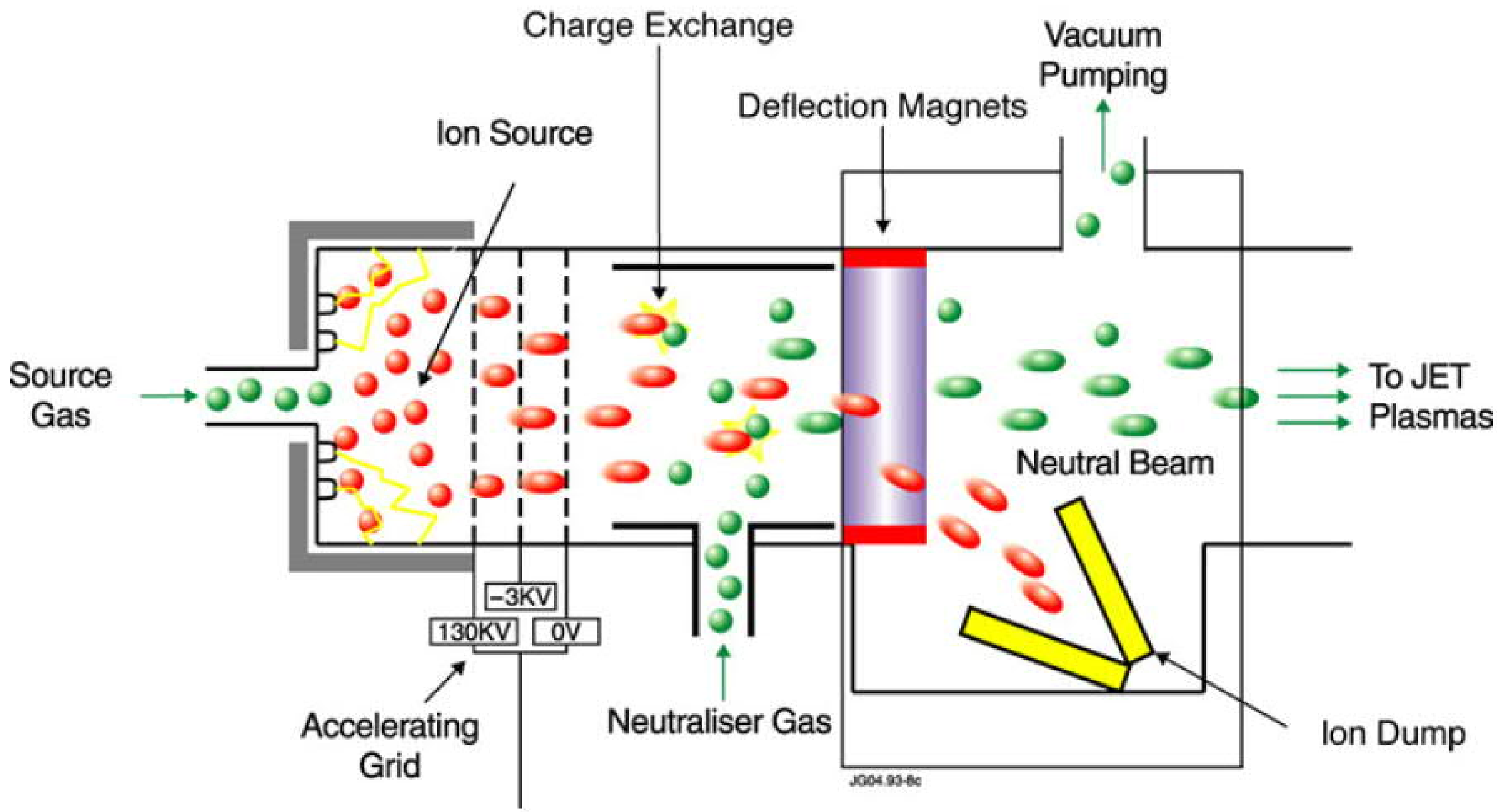
Yleismies Jantunen rööreja tsiikaamassa

Total heating power **50 MW …**

Heating methods:
neutral beams and RF waves



Working principle of a neutral beam

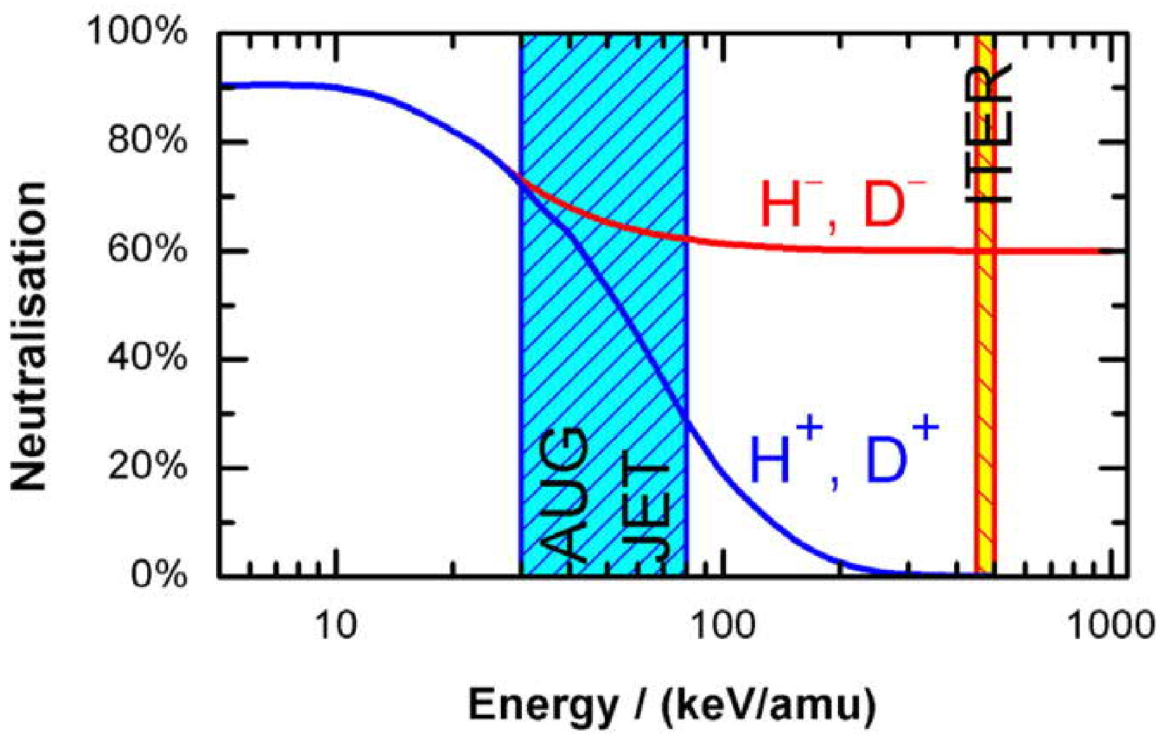


What are *negative* neutral beams? And why?

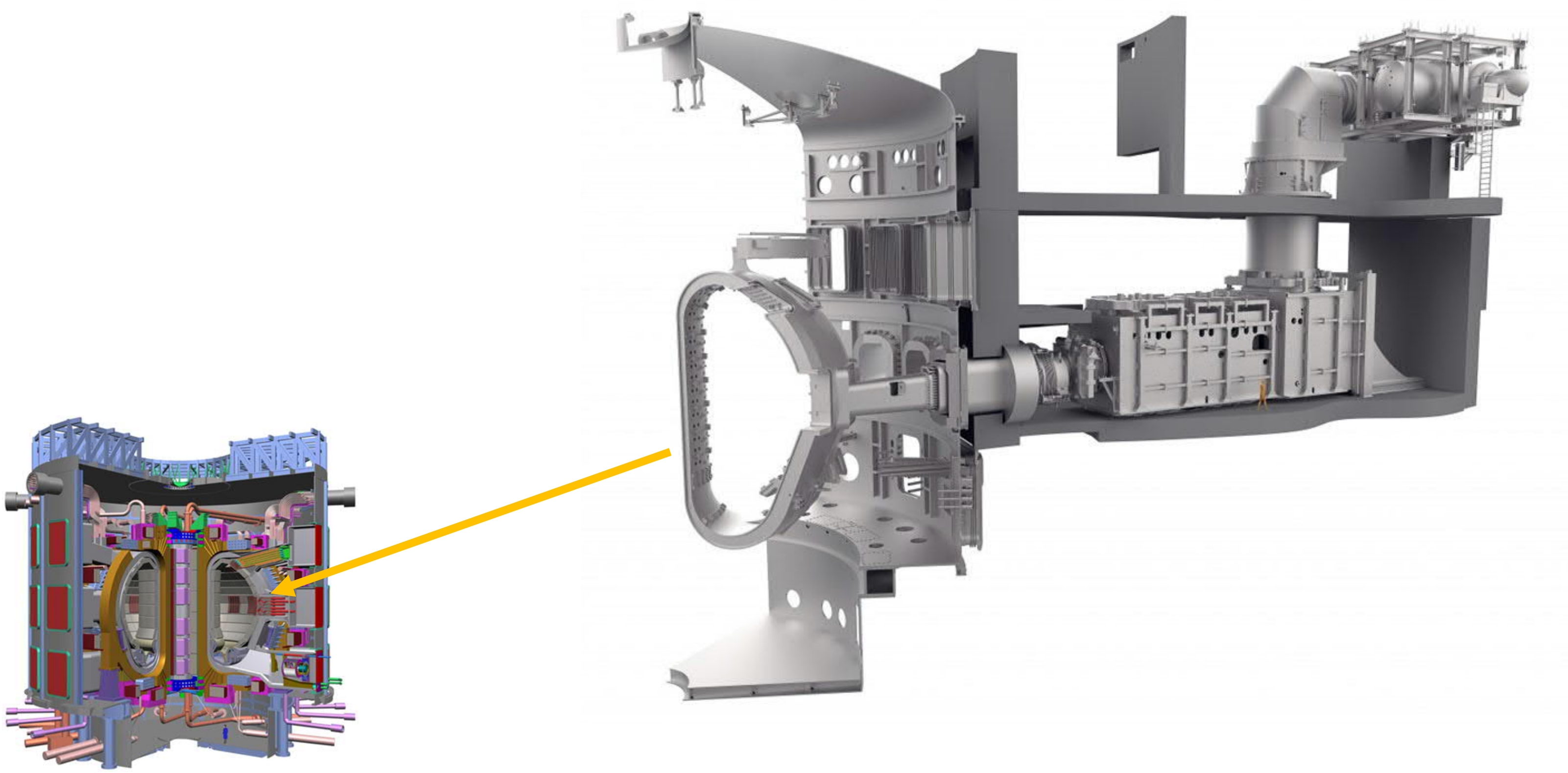
The beam energy determines
- Deposition depth in the plasma
- The amount of *shine-through*

Also the direction of the beam affects both deposition and shinethrough

$E_{NBI} > 20T_e$ ➔ fast ions born from beams slow down predominantly on *electrons*



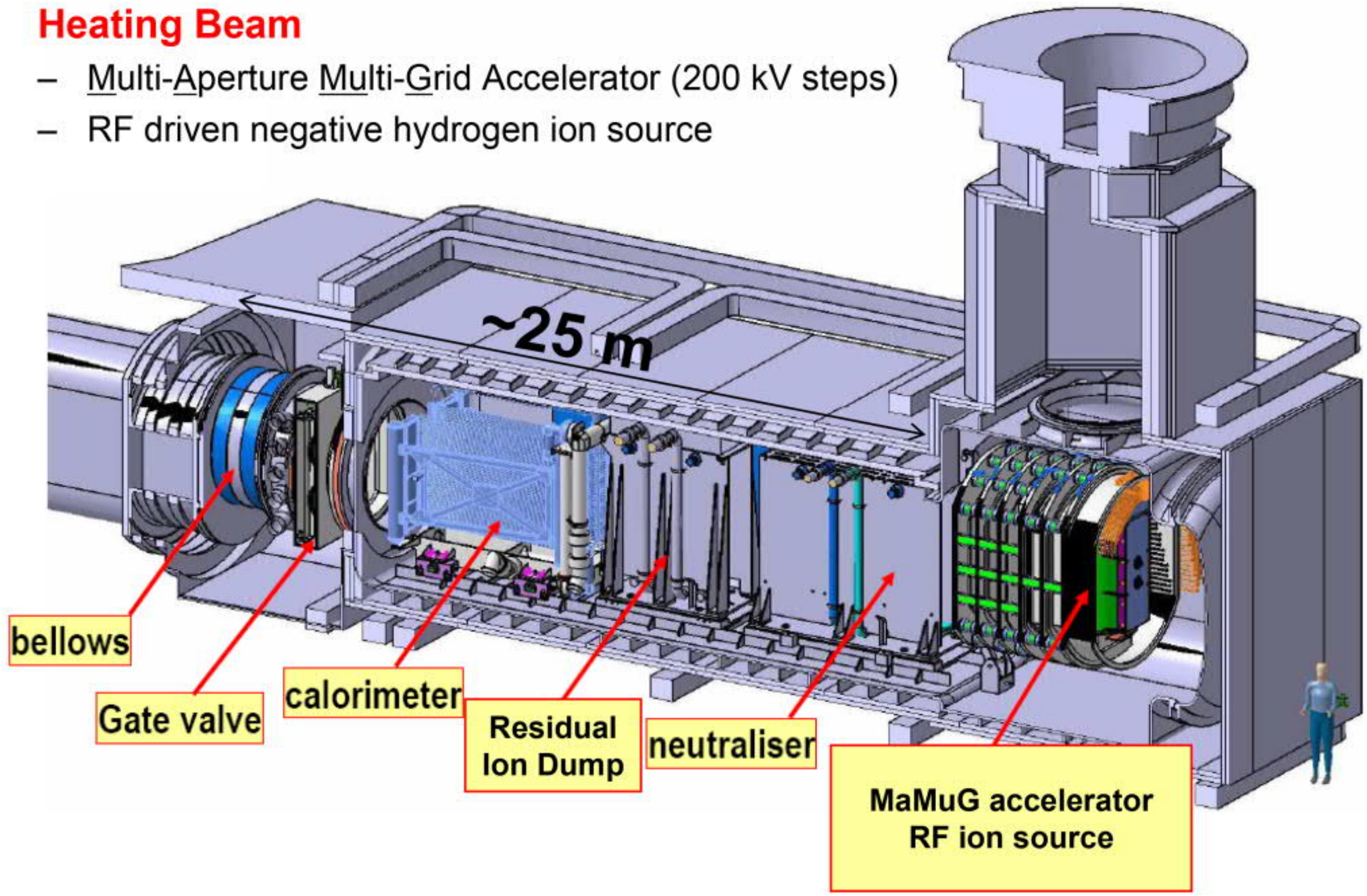
ITER NBI – notice the size …



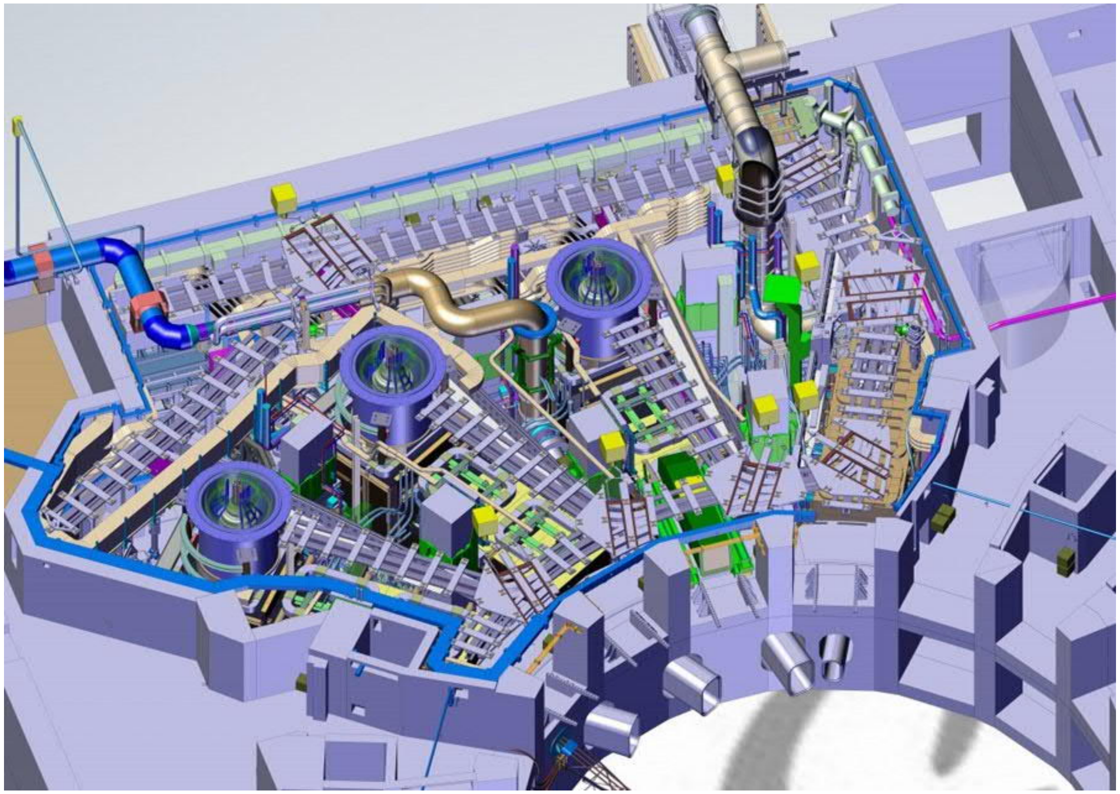
Beam box

Heating Beam

- Multi-Aperture Multi-Grid Accelerator (200 kV steps)
- RF driven negative hydrogen ion source



ITER: 3 injectors, 3 directions



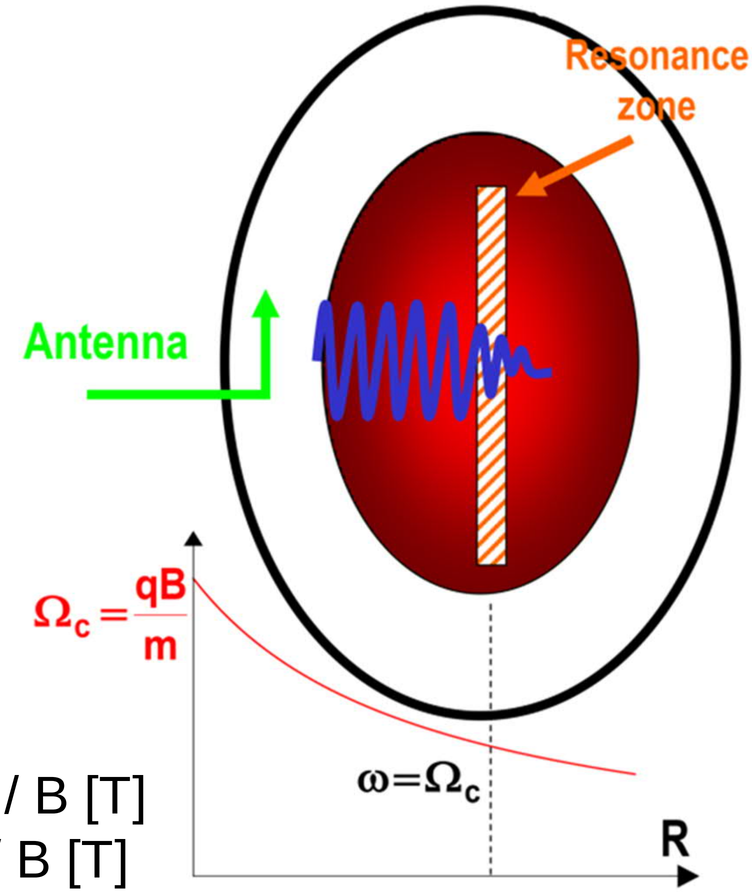
NBIs around the world …

Fusion device	AUG		W7-X*	JET	LHD	JT-60U		ITER
Beam species	H^+/D^+	H^+/D^+	H^+/D^+	H^+/D^+	H^-	H^+/D^+	H^-/D^-	H^-/D^-
Type of source	Arc	RF	RF	Arc	Arc	Arc	Arc	RF
Extraction area (cm^2)	390		390	300	1150	128	1660	2000
Max. energy (keV)	55/60	72/93	55/60 (72/100)	80/130	180	75/95	360/380	1000
Injected power per source (MW)	1.6/2.5	1.4/2.5	1.4/2.5	1.5/1.4	3.75	0.9/1.4	3.3/2.7	16.7
Sources per beamline	4		1 (4)	8	2	2	2	1
Number of beamlines	1+1		2	3	3	14	1	2
Total power (MW)	12/20		2.8/5 (11.2/20)	36/32	15	27/40	13.2/10.8	33
Pulse duration (s)	4/8	4/8	10	10	10	5	10	3600
Max. current density (mA/cm^2)	250/200	160/160	250/200	160/160	35	270/210	13/9	24/20

RF heating

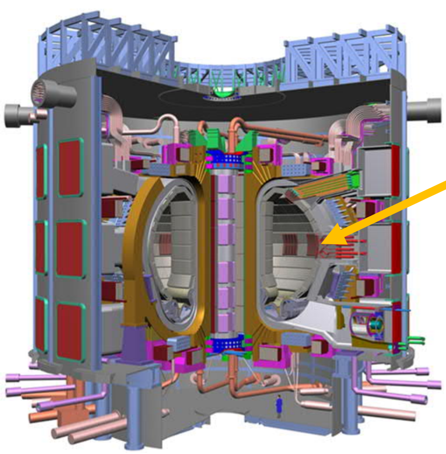
Basic idea:

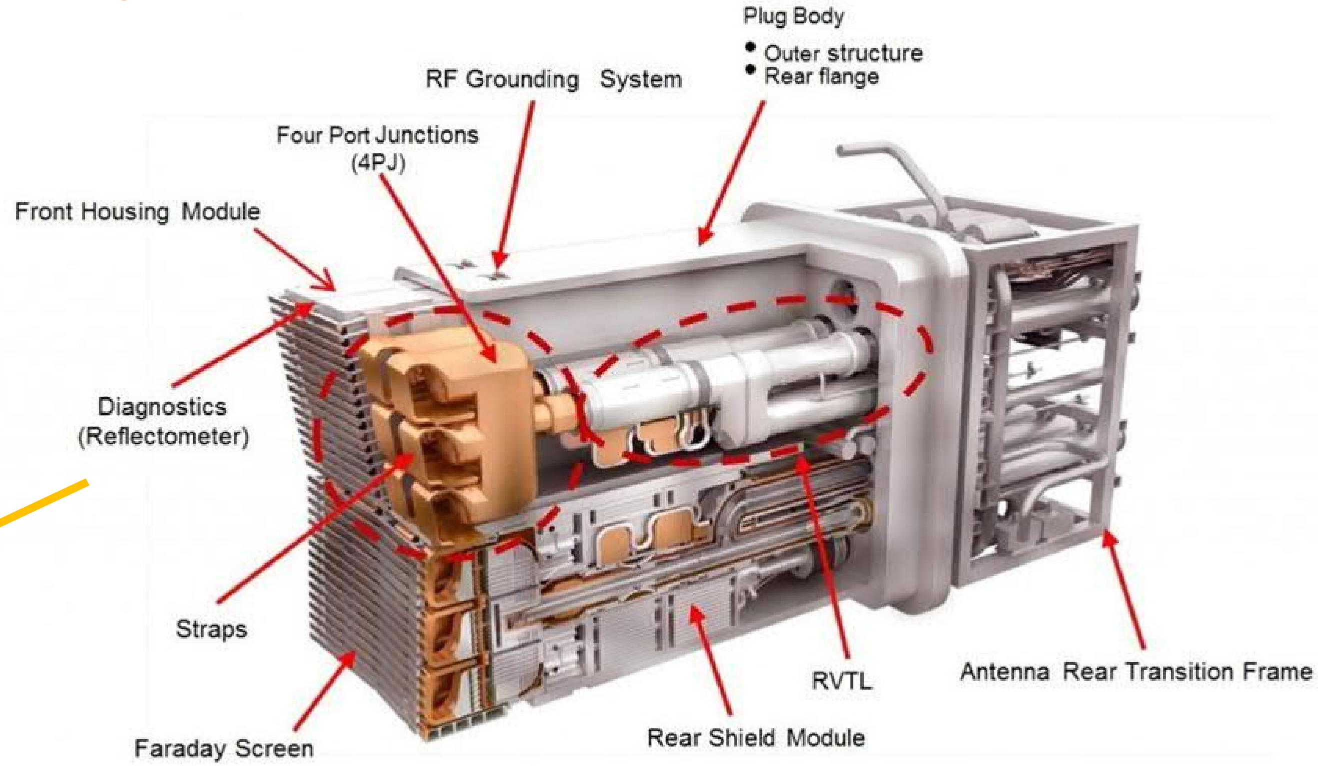
- Excite an RF wave at frequency ω close to plasma edge
- Wave propagates in plasma (non-trivial)
- Wave gets absobed at a resonance layer where $\omega = \Omega_e$ or Ω_i
- Particles accelerated by the wave transfer the energy to bulk plasma thus heating it up



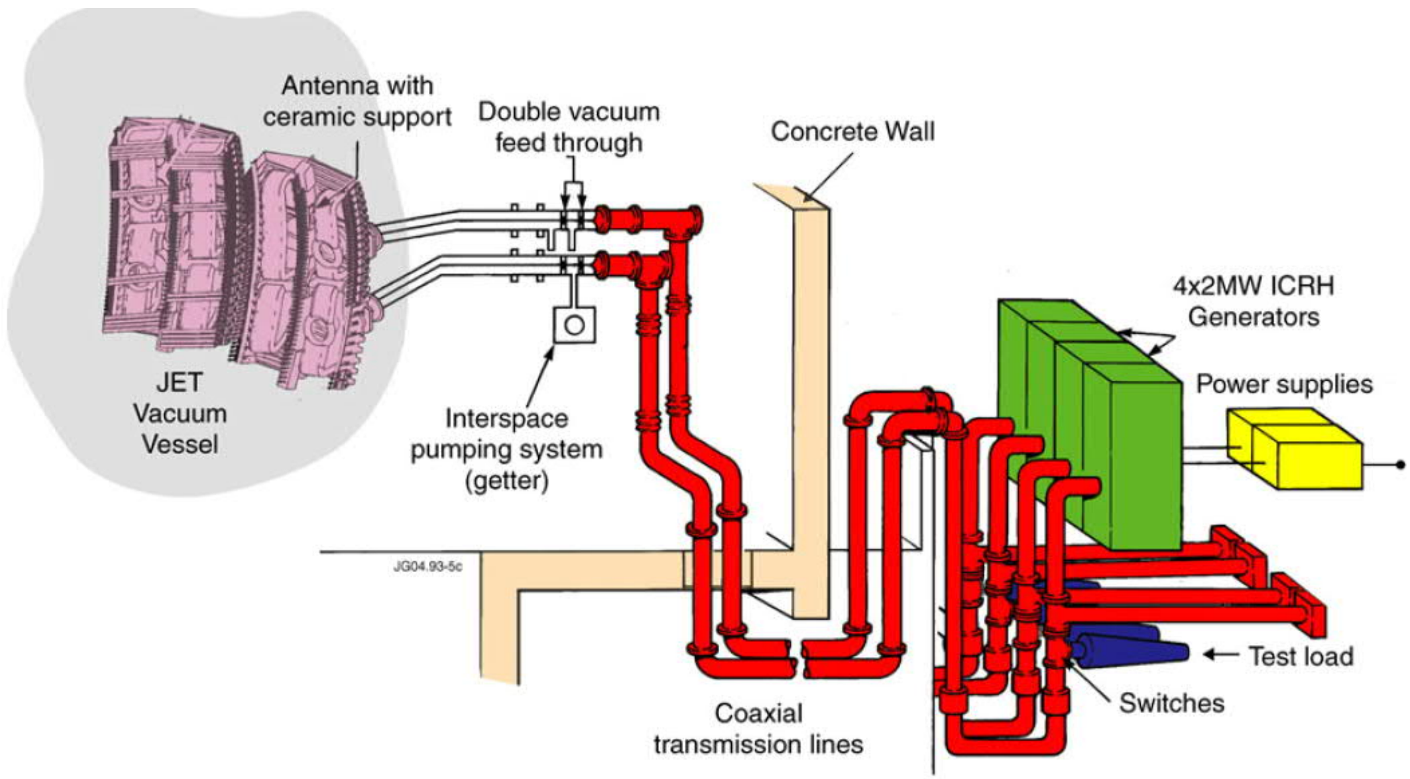
ECRH: ω ~ 28 GHz / B [T]
ICRH: ω ~ 15 MHz / B [T]

ITER ICRH antenna





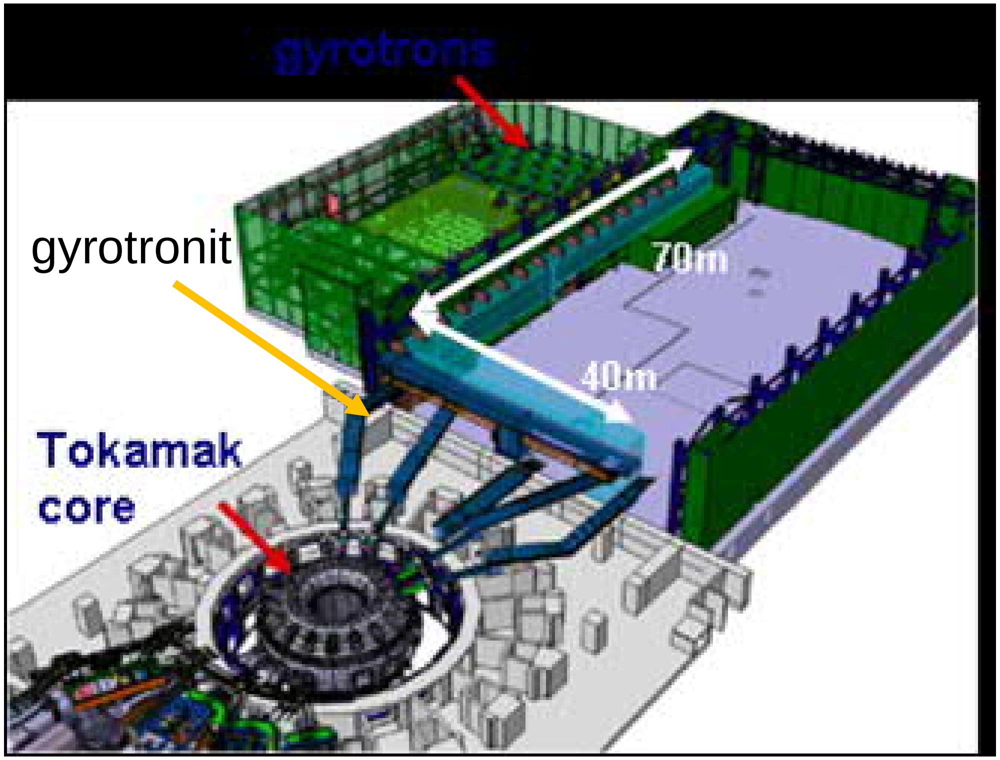
JET ICRH system: 4 x 2 MW



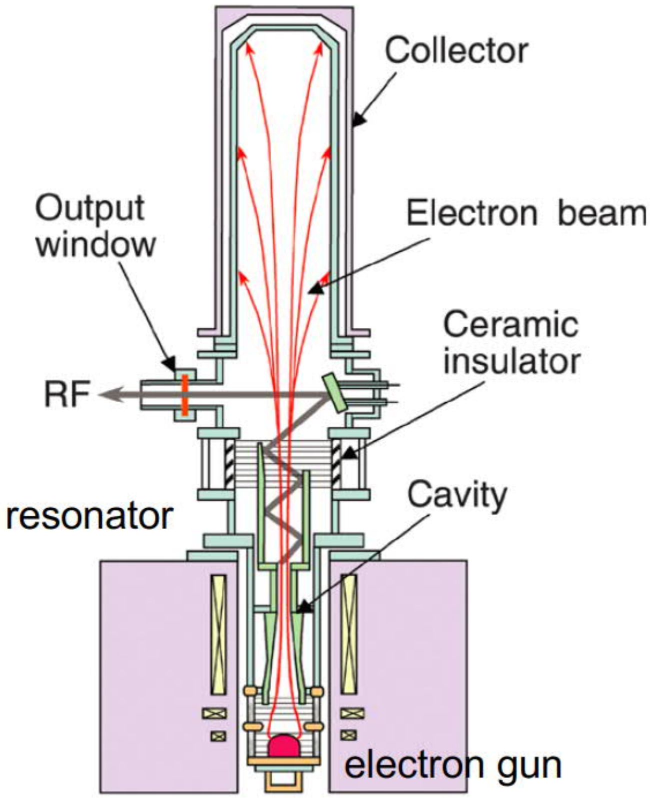
ITER ECRH system

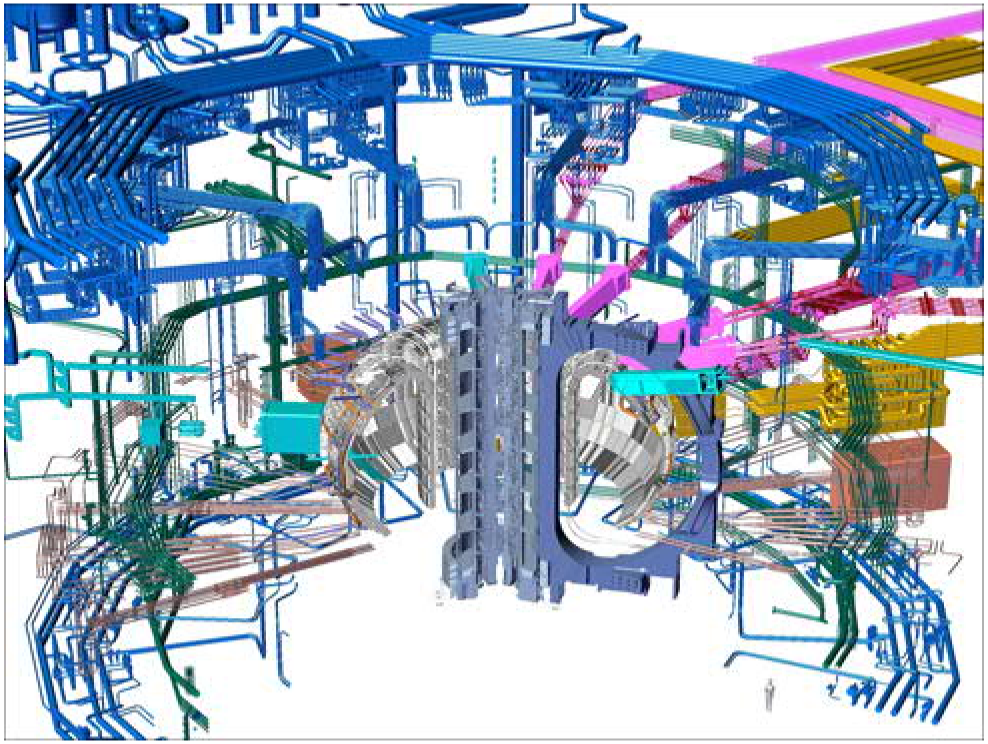
Key words:

- Gyrotron
  - RF source
- Wave guide
  - Transfers the power to the plasma

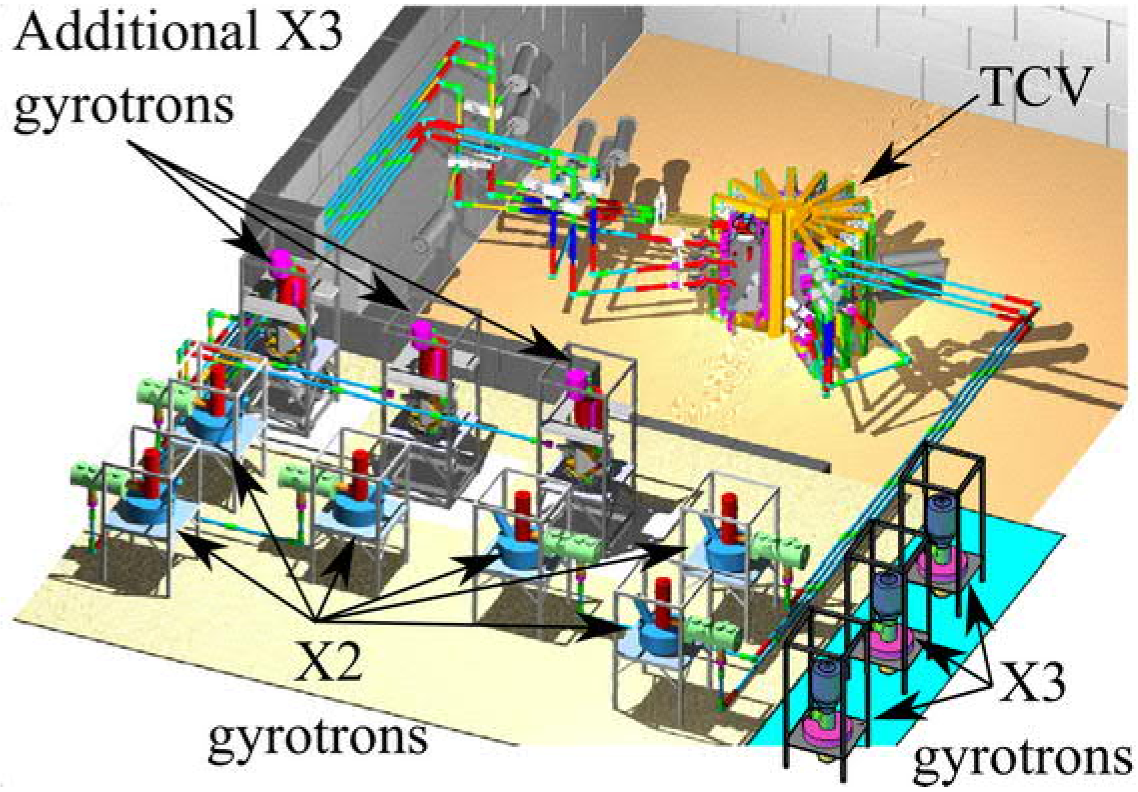


Gyrotron and pink wave guides





ECRH system @ EPFL, Switzerland

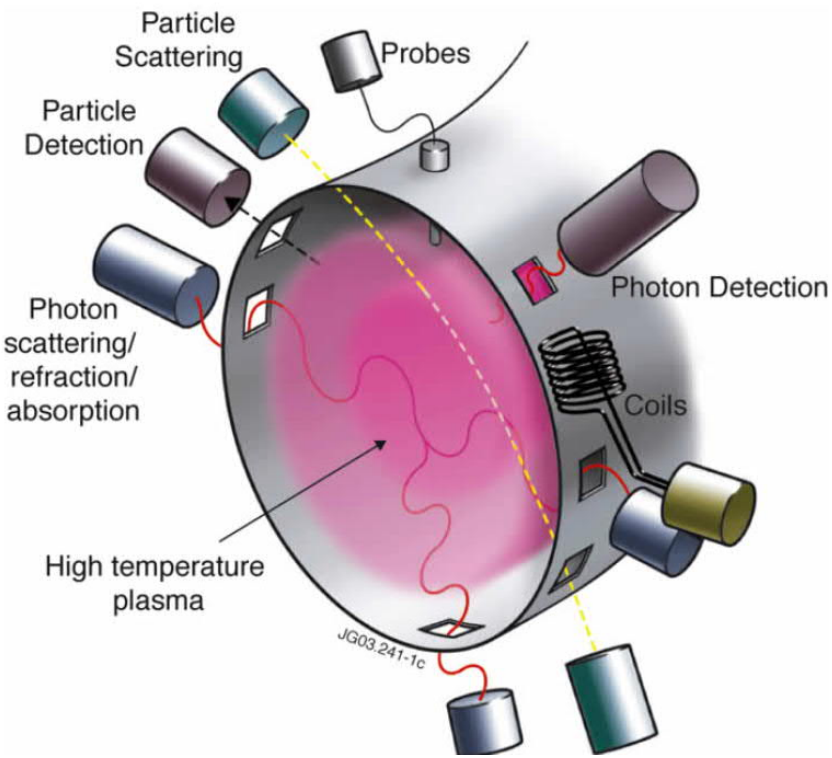


Summary of the heating methods

Scheme	Advantages	Limitations
Ohmic heating	Efficient	Cannot reach ignition conditions, not suitable for stellarator
Neutral beam injection	Reliable	Close to torus, large ports, negative ions necessary
Ion cyclotron resonance	Central heating	Antenna close to plasma, coupling efficiency
Electron cyclotron resonance	Reliable, flexible, localized heating + current drive	Cutoffs, electron heating ⇒ needs strong coupling to ions

How to measure = diagnose a plasma?

What possibilities do we have?



We can measure:

- Radiation from the plasma
- Particles escaping the plasma
- Changes in the magnetic field by external current loops
- Physical probes at the VERY plasma edge for a SHORT while

Measuring plasma density

- Thomson scattering:
  - Shoot a laser beam to plasma and measure its attenuation/reflection
  - *Active* diagnostic: measuring point determined by the intersection of the source and detector lines
- Interferometry
- Langmuir-probes at the very edge (SOL)

Measuring plasma temperature: e^-

- Thomson scattering
  - Shoot a laser beam to plasma and measure its Doppler broadening
  - *Active* diagnostic: measuring point determined by the intersection of the source and detector lines
- Langmuir-probes at the very edge (SOL)

Measuring plasma temperature: i^+

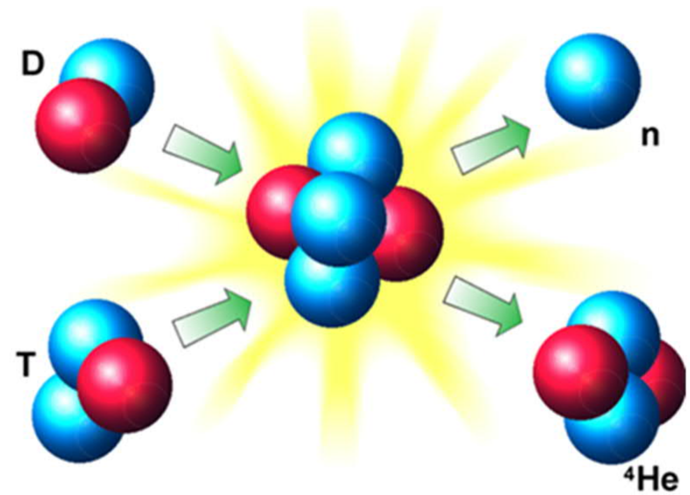
- NPA = neutral particle analyzer
  - Passive: signal along the entire line of sight ☹
- CXRS: Charge exchange resonance spectroscopy
  - Broadening of the impurity spectral lines gives the temperature!
  - Passive: signal along the entire line of sight ☹
- Active CXRS:
  - Diagnostic NBI ➔ location determined by the intersection of the NBI and the line of sight

Measuring plasma rotation: i^+

- CXRS: Charge exchange resonance spectroscopy
  - The Doppler *shift* of the impurity spectral lines gives the motion of the plasma!
  - Passive: signal along the entire line of sight ☹
- Active CXRS:
  - Diagnostic NBI ➔ location determined by the intersection of the NBI and the line of sight

Measuring fusion production

- Fission chamber (sees neutrons)
- Neutron camera
- Neutron spectrometer
- Endothermic nuclear reactions with impurities ➔ gamma radiation



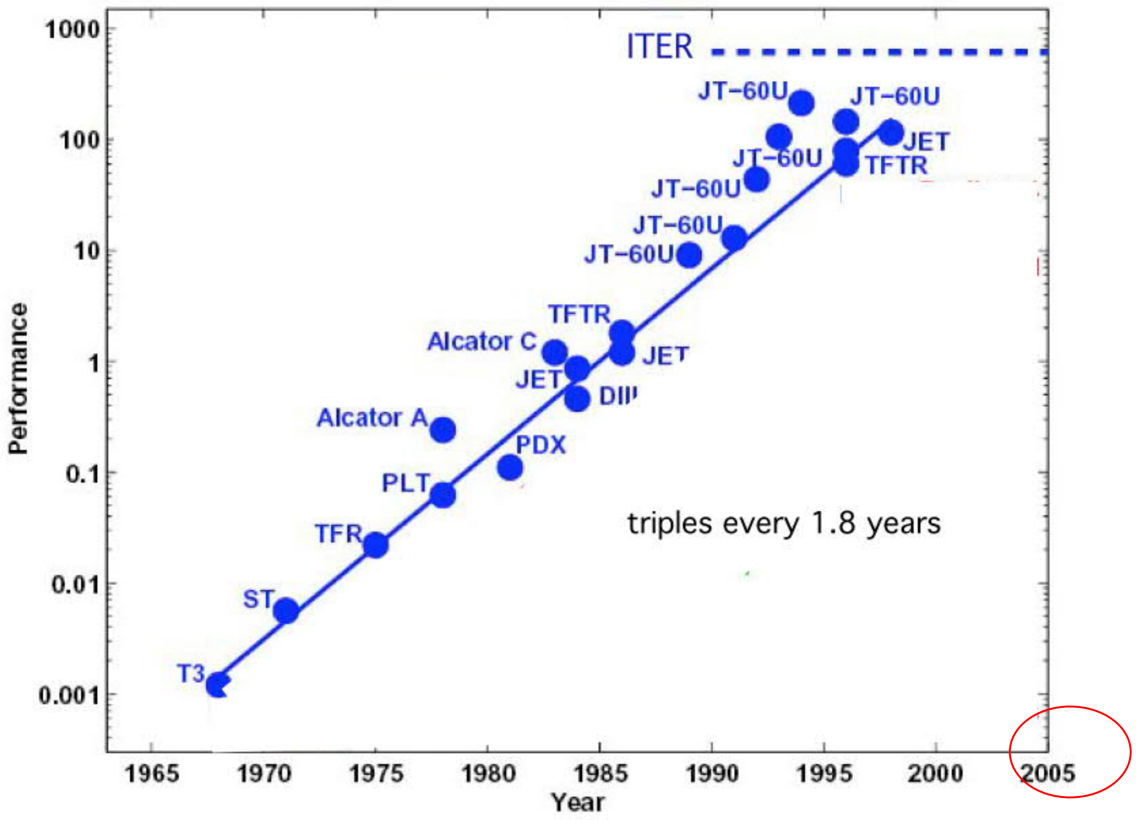
D + T
→ ^4He + n + 100 000 kWh/g

Summary of the diagnostic methods

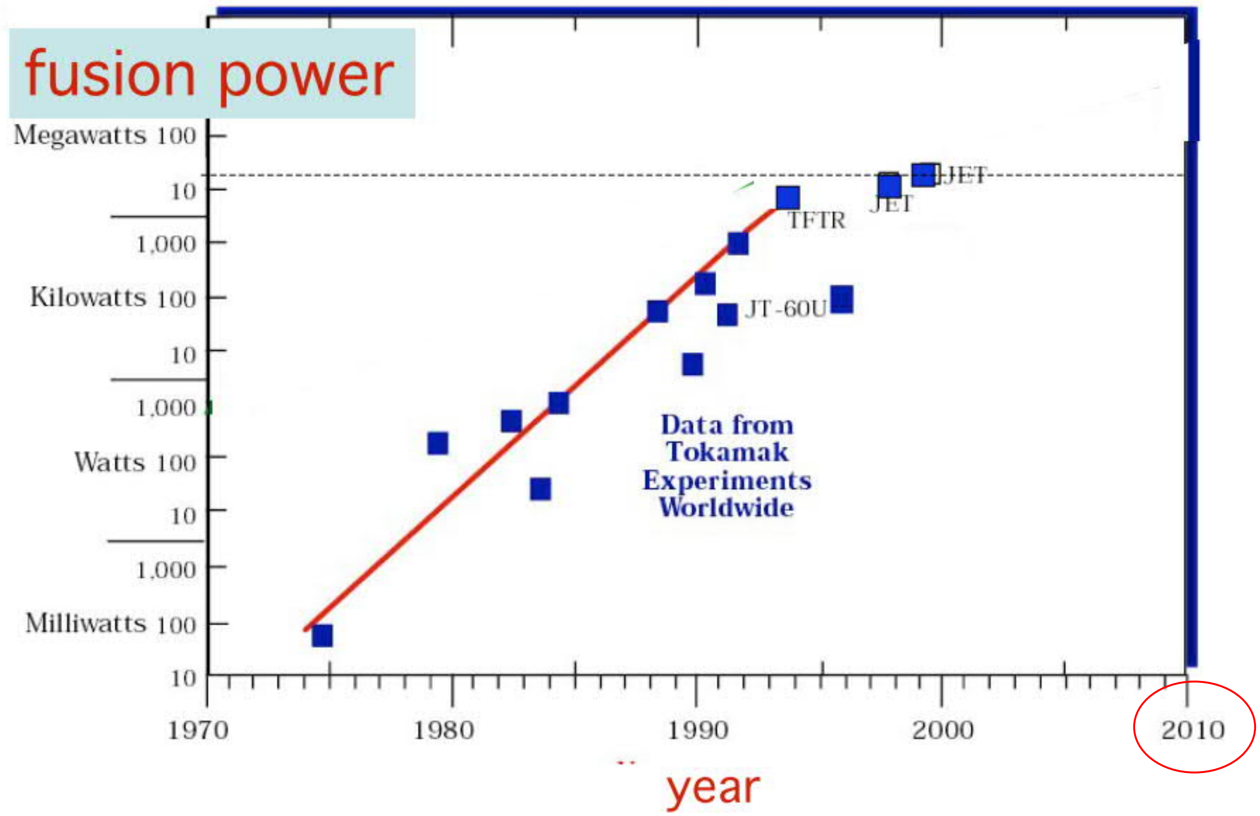
Category	Parameter	Method
Magnetics	Plasma current Loop voltage (Ohmic power, T_e) Diamagnetic energy Plasma position/equilibrium	Rogowski coil Voltage loops Diamagnetic loop Poloidal field coils
Passive radiation	Electron temperature and densities, total radiation, Bremsstrahlung, line radiation (including impurities → impurity influxes), surface heating power	Electron cyclotron emission, VUV and visible spectroscopy, soft x-rays, bolometry, thermography
Active radiation	Electron density and temperature, current profile, ion temperature,	Thomson scattering interferometry, reflectometry, polarimetry, charge exchange, Li or He beams, heavy ion probe
Particle diagnostics	Neutron yields, particle fluxes	Fission chambers, neutron cameras, Langmuir probes

Where are we now?

Plasma performance as $nT\tau_E$



Progress as MW …



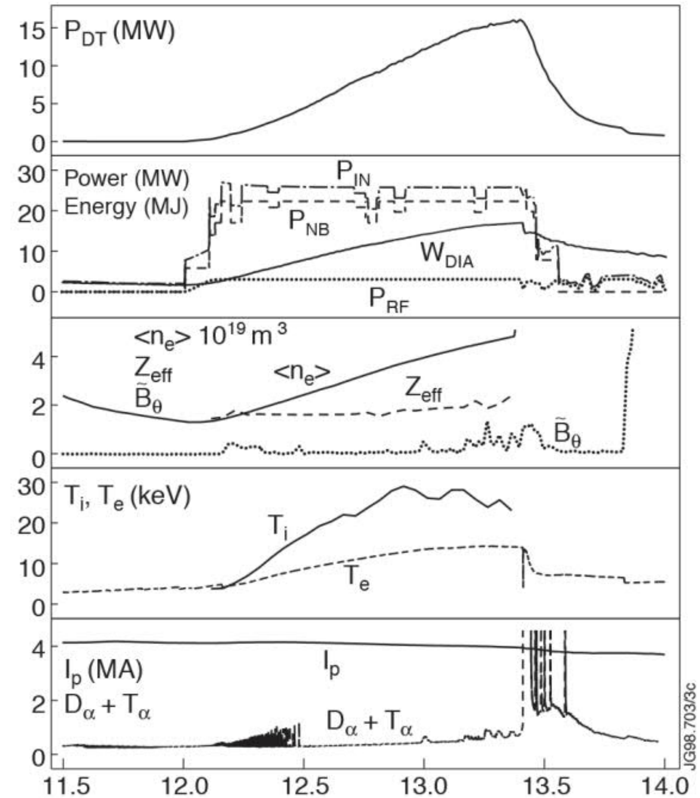
Breakthroughs in fusion research

- From bottle to donut (design in 50’s, demo in ‘68)
- L-H transition (experimental discovery, ‘82)
- DT experiments (late 90’s) = verification of fusion:
  - TFTR (1993): P_{fus} = 10.6 MW
  - JET (1997): P_{fus} = 16.1 MW (Q ~ 0.7)
- Anomalous transport = micro turbulence (theory, 00’s)
- ITER = International Thermonuclear Experimental Reactor (under construction 2010 -- 2020’s)

Fusion 'world record' 1997: 16.1MW

- Continuous increase in P_{DT} with heating power (of total 25.4 MW) ⇒ $P_{fus}/P_{aux} \approx 0.64$ at the end of discharge (transiently, limited by heating systems)
- Carbon is the primary impurity species ($Z_{eff} \approx 2$)
- "Hot ion" H-mode: $T_i > 2 \times T_e$

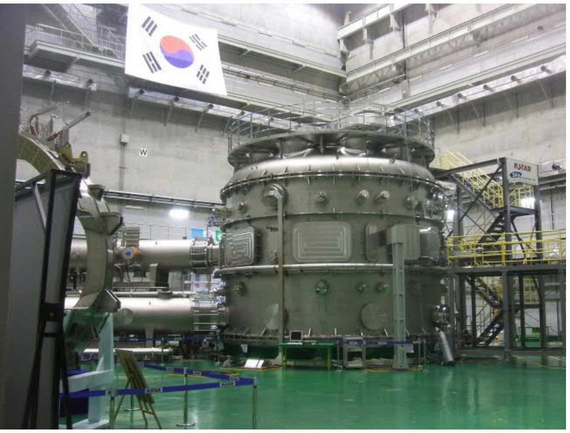
DTE2 ongoing 2021 … new type of record still held by news embargo… ☺



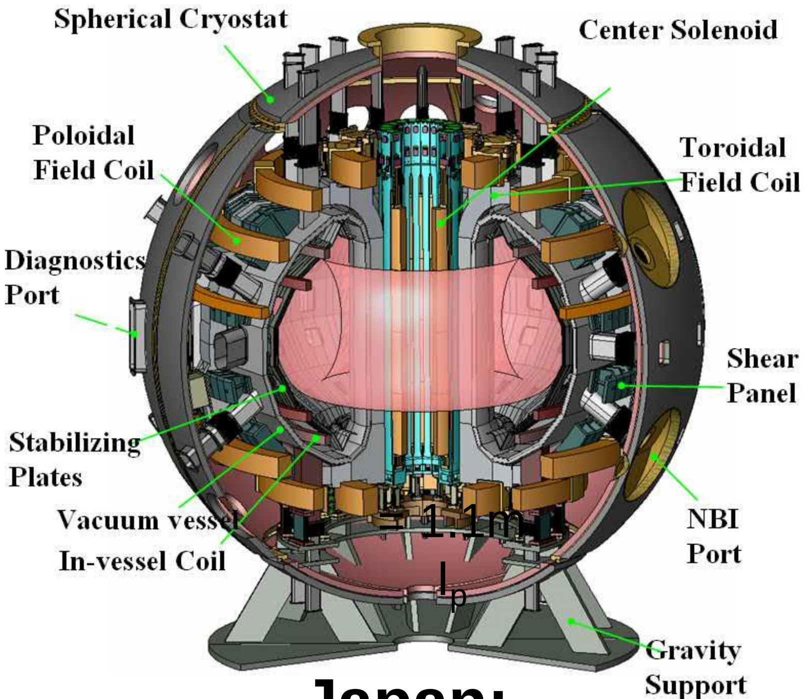
M. Keilhacker, et al., NF 1999

But JET is already very old an fragile …
don’t we have something new and better?

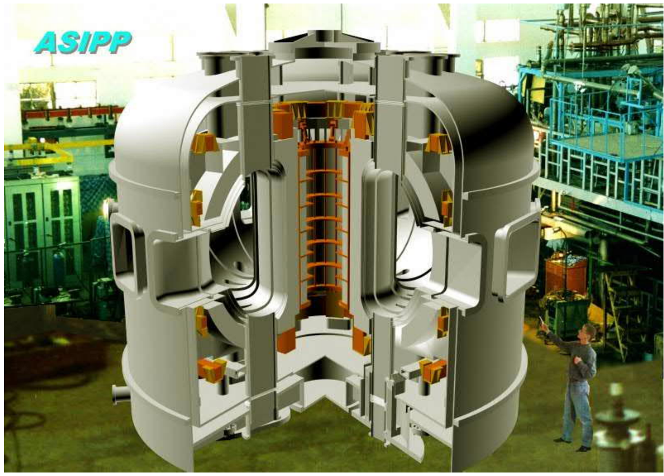
Far East



South Korea:
KSTAR
R = 1.8m
a = 0.5m
I_p = 2MA
B_T = 3.5T

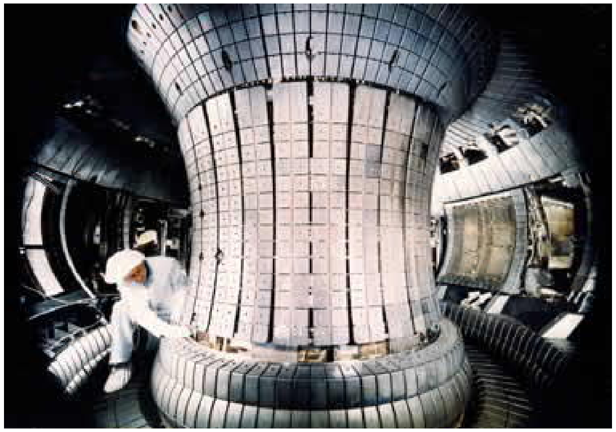


Japan:
JT-60SA (SC)
satellite tokamak for ITER
R = 3m, a = 1.1m, I_p = 5.5MA, B_T = 2.8T

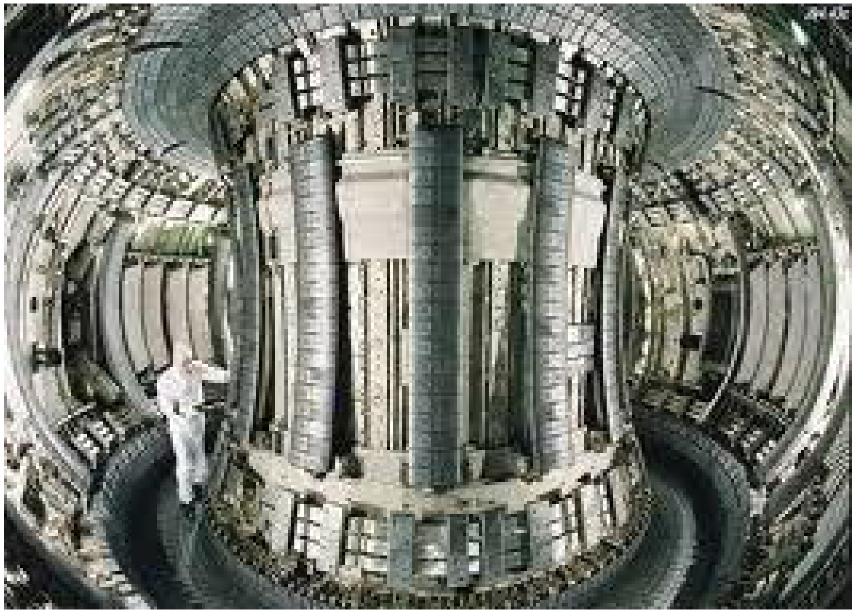


China:
EAST
R = 1.7m,
a = 0.4m
I_p = 0.5MA
B_T = 3.5T

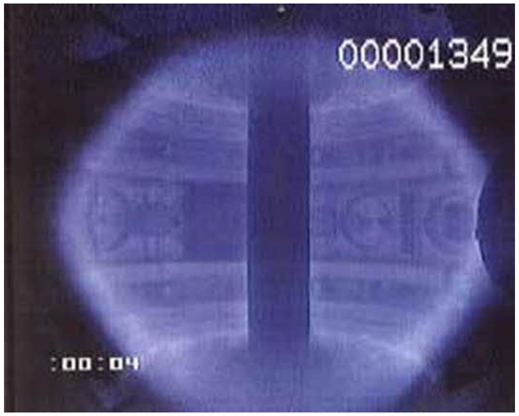
Europe



ASDEX Upgrade
IPP-MPG, Garching, Germany
Specialized in PWI: high P/A
R = 1.7m, a = 0.6m
I_p = 5.5MA, B_T = 3.1T



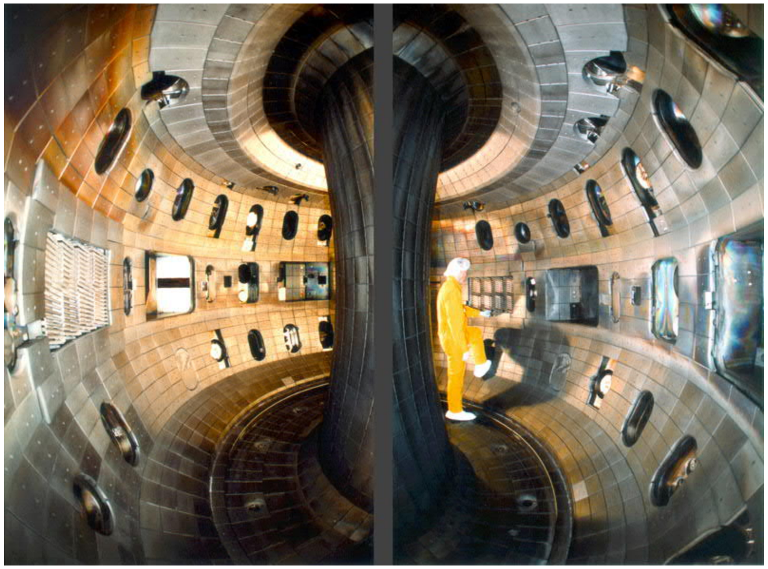
JET
Culham, England
LARGE, high performance
R = 3m, a = 1.3m
I_p = 4.8MA, B_T = 3.5T



MAST
Culham, England
'spherical tokamak'
R = 0.85m, a = 0.65m
I_p = 1.3MA, B_T = 0.6T

Additionally smaller, more specialized machines:
Tore Supra = WEST *(France)*, ***TCV*** *(Switzerland)*...

USA

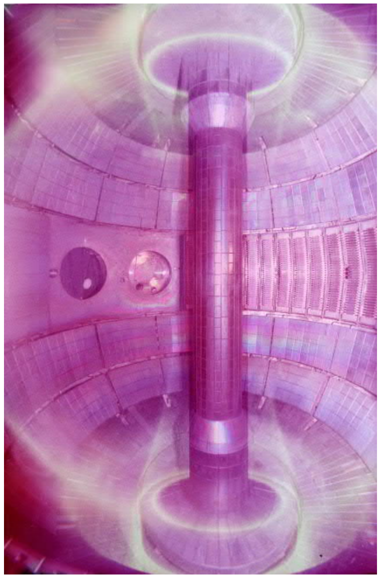


DIII-D

General Atomics

R = 1.7m, a = 0.7m

I_p = 2MA, B_T = 2.2T



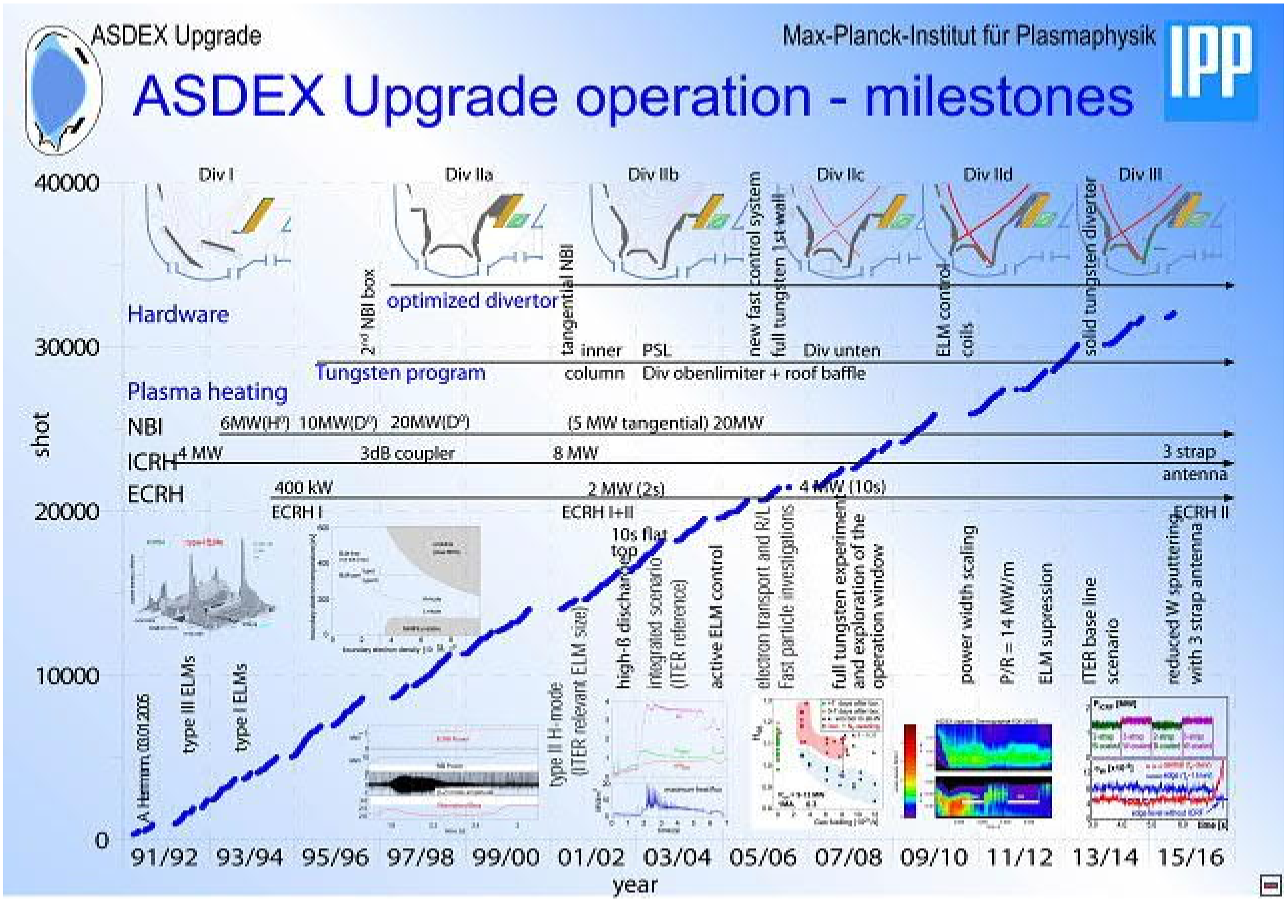
NSTX-U

Princeton

R = 0.85m, a = 0.68m

I_p = 1.4MA, B_T = 0.3T

… but being fixed for N years… ☹

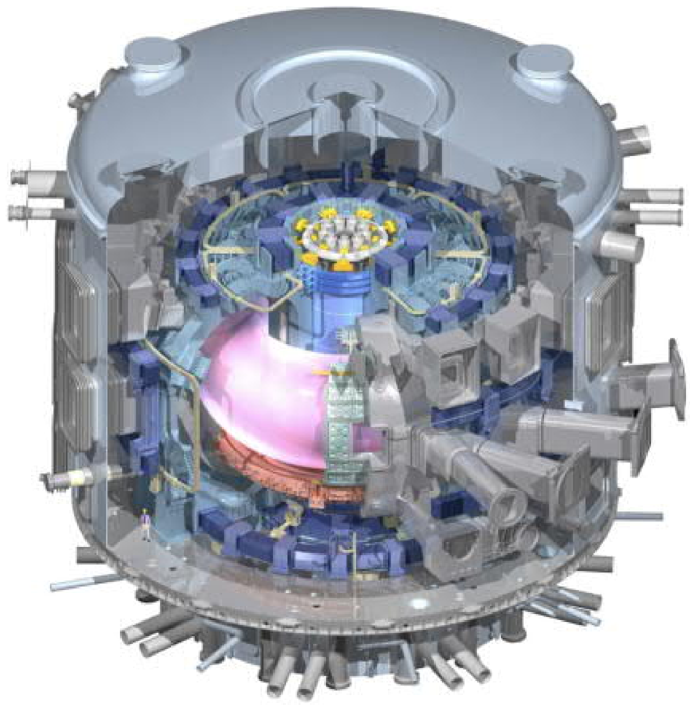


http://www.ipp.mpg.de/1728289/panorama : AUG

And our goal is … *energy !*

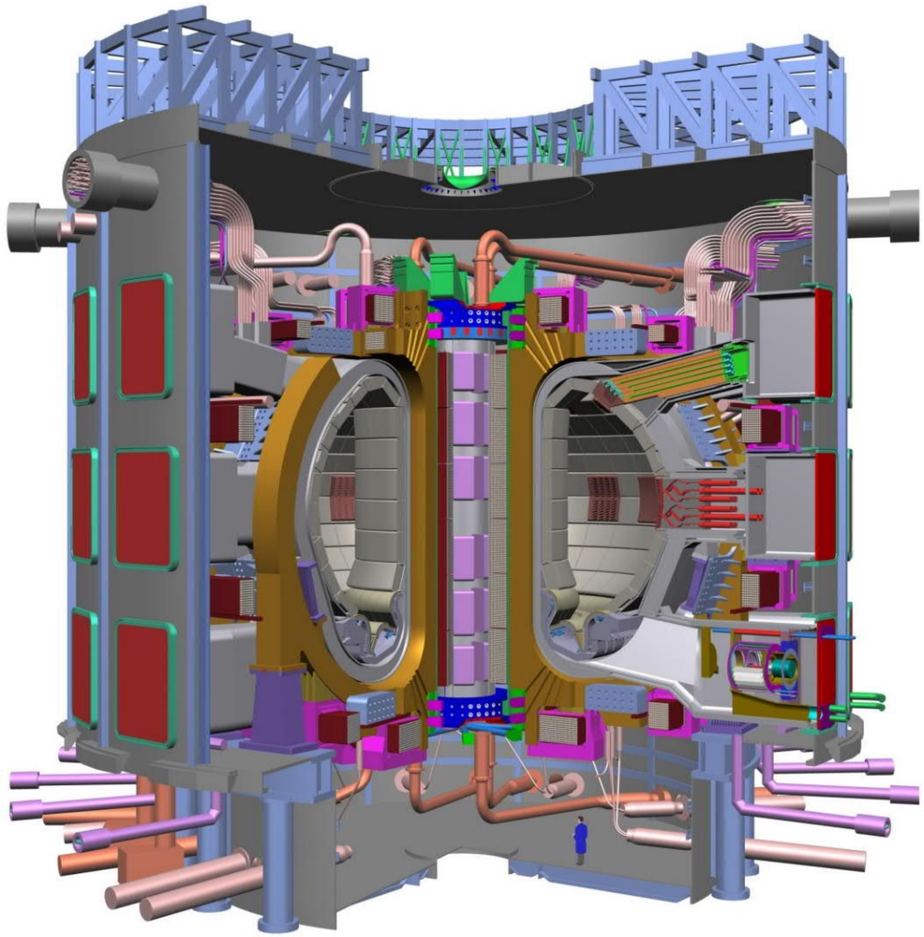
ITER = the first fusion *reactor*

	JET	ITER
Size	3 m (15 x 15m)	6.2 m (30 x 30m)
Magn. field	3.4 T	5.3 T
Plasma current	5 MA	17 MA
SC coil system	No (copper)	Yes ⇒ cryostat
P_{aux}	38 MW	50 MW
P_{fusion}	16 MW	500 MW
dpa		1 / 20 yrs



ITER specifications

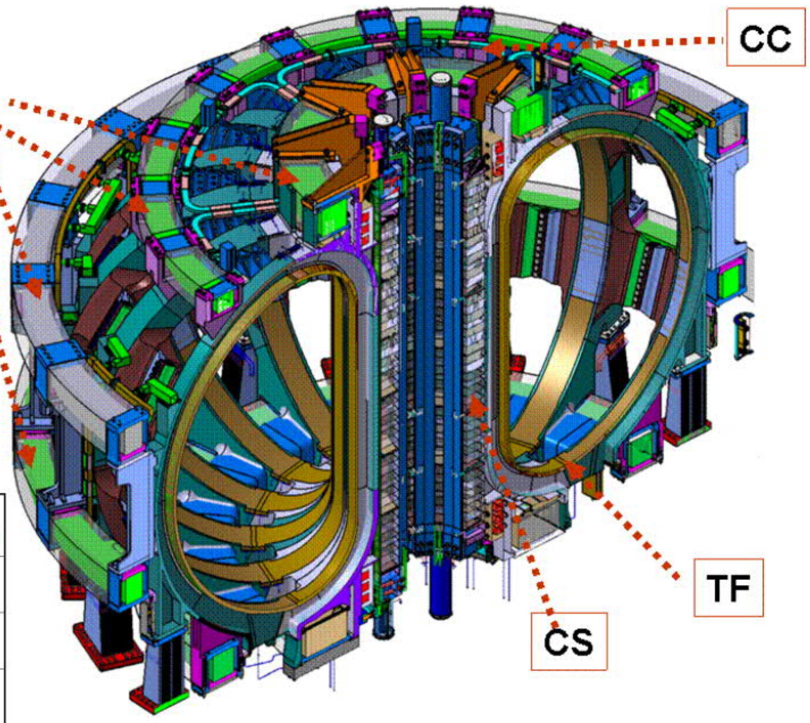
- Plasma conditions similar to expected power plant
- Technical specs:
  - Total fusion power: 500 MW
  - Q = Fusion power/aux. heating power ≥ 10
  - Plasma major radius: 6.2 m
  - Plasma minor radius: 2.0 m
  - Plasma current: 15 MA
  - Toroidal field at 6.2 m: 5.3 T
  - Plasma volume: 837 m^2
  - Installed auxiliary heating: 73 MW
- Cost: 5 + 5 + 0.5 = 10.5 billion (building + operation + decommission) … heh heh …



Yleismies Jantunen röörejä tsiikaamassa

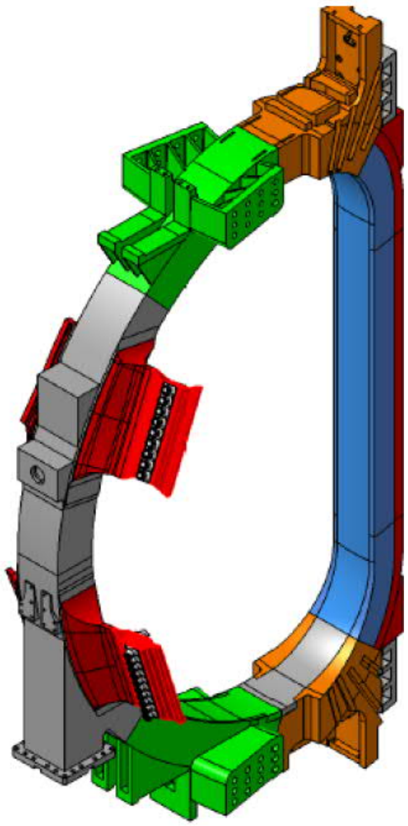
ITER is not a small device …

- 18 toroidal field coils
- 6 central solenoid modules
- 6 poloidal field coils
- 9 pairs of correction coils



System	Energy GJ	Peak Field	Total MAT	Cond length km	Total weight t
Toroidal Field TF	41	11.8	164	82.2	6540
Central Solenoid	6.4	13.0	147	35.6	974
Poloidal Field PF	4	6.0	58.2	61.4	2163
Correction Coils CC	-	4.2	3.6	8.2	85

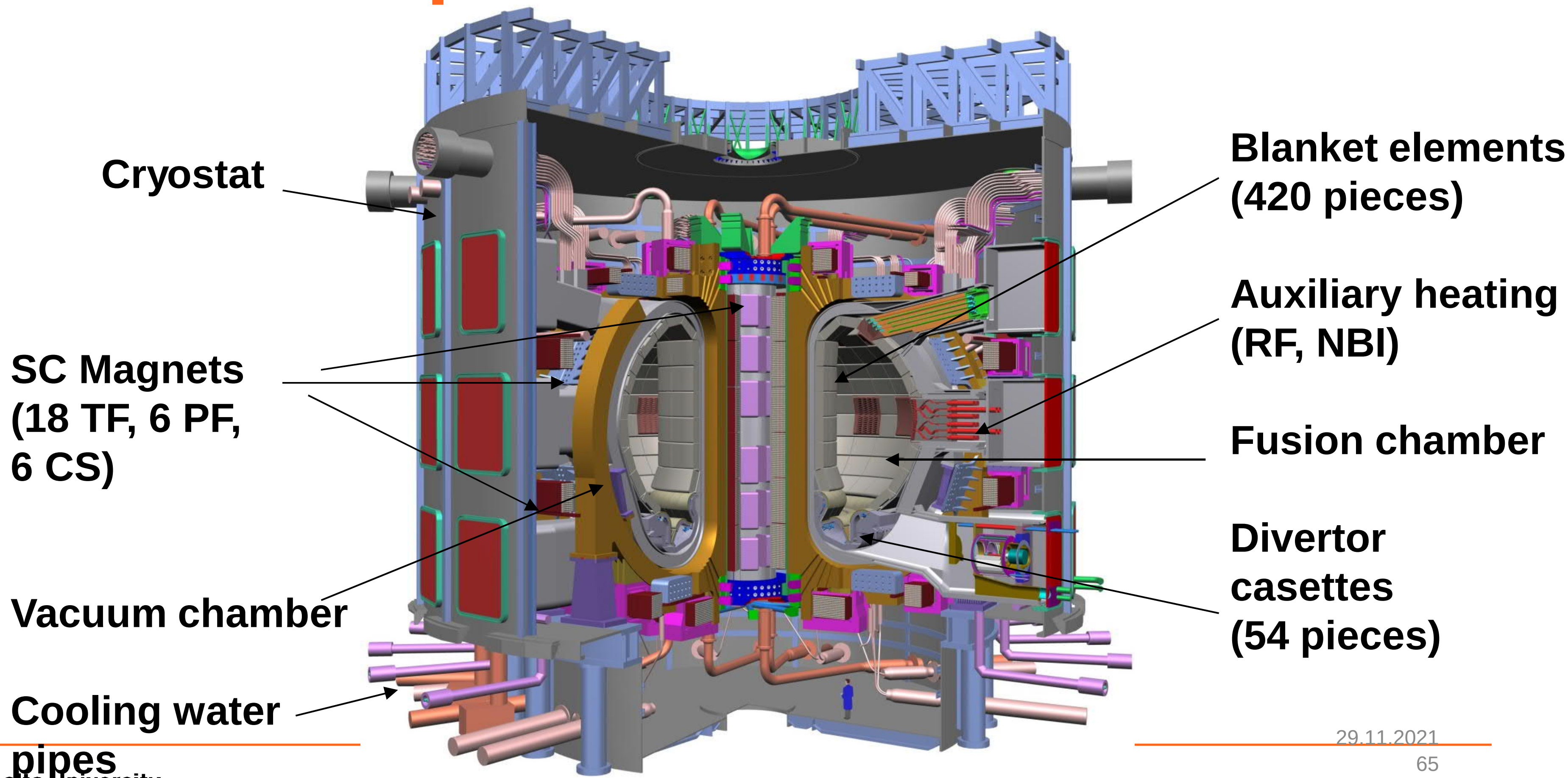
A TF coil vs Boeing 747-300 …



TF coil: 360 t

Boeing 747-300: (maximum takeoff weight ~377 t)

ITER main components



ITER construction site 2011

ITER Construction site Dec 2012

Aalto University
School of Science

ITER Construction site Feb 2015

Iter.org

ITER Construction site Feb 2016

Iter.org

April 2016

December 2017

Nyt on jo siirrytty sisätöihin ….

Now JT-60SA deserves another look …

ITER: new & needs

Very high plasma current, 15MA

- Generation and control of runaways?

High energy *negative* neutral beams: 33 MW of 1 MeV N-NB

- Reliability? Performance?

Large 3.5MeV alpha population

- Effect on equilibrium and stability
- Diagnostics for *confined* energetic particles badly needed

Long pulses (up to 1000s)

Test blankets for tritium breeding

What JT-60SA can offer

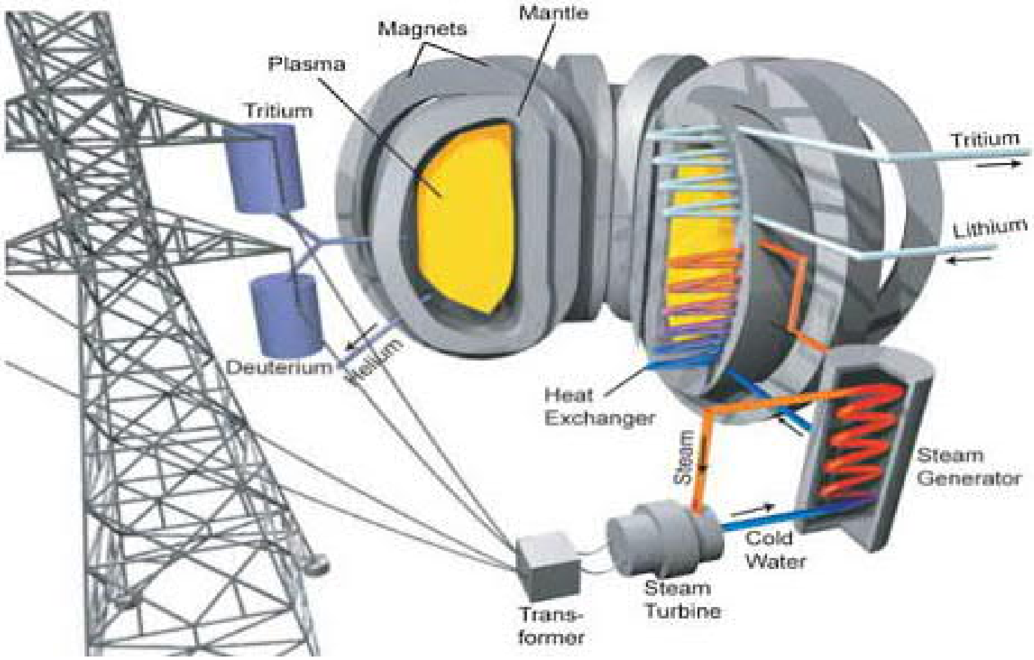
- High plasma current: up to 5.5 MA
- High energy *negative* neutral beams: 10 MW of 500 keV N-NB
- super-conducting coils ➔ long pulses (100s)
- Two sizes of TBM mock-ups (?)

- Additional *important* benefit: as a joint European-Japanese device, it will prepare us for multi-cultural use of high tech scientific devices (not easy…)

And our goal is … *electricity !*

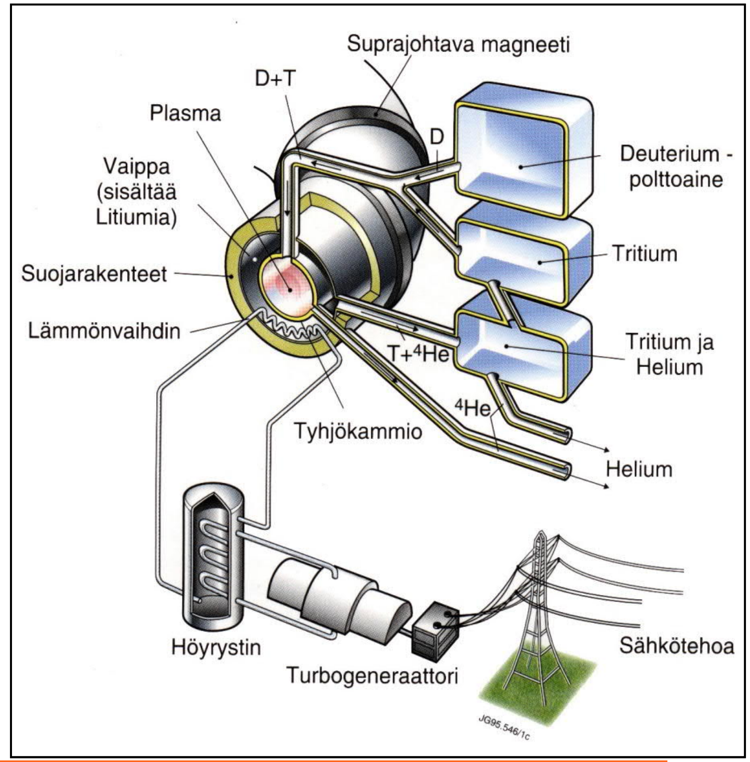
Aalto University
School of Science

DEMO – replace diagnostics by power plant components!



Fusion reactor = ”steam kettle” - operating temperature 100 million deg …

- feed D-T gas to reactor chamber
- Heat to fusion temperature
- Reactions start ➔
- 3.5 MeV fusion alphas stay and heat
- 14.1 MeV n’s transport power out of the magnetic cage and heat the water in the cooling pipes within the walls
- Cooled-down He ash led to the *divertor*
- Breed more T: fusion neutrons + Li in the reactor blanket
- Something fails ➔ fusion conditions are lost ➔ burn is quenched



Various designs: DEMO-CREST based on ITER @P_{fus} = 10xP_{aux}; ARIES-AT, EU PPPT

• Escalated engineering challenge compared to ITER:

- Fusion material and their limits: neutron fluxes (up to 100 dpa/yr)

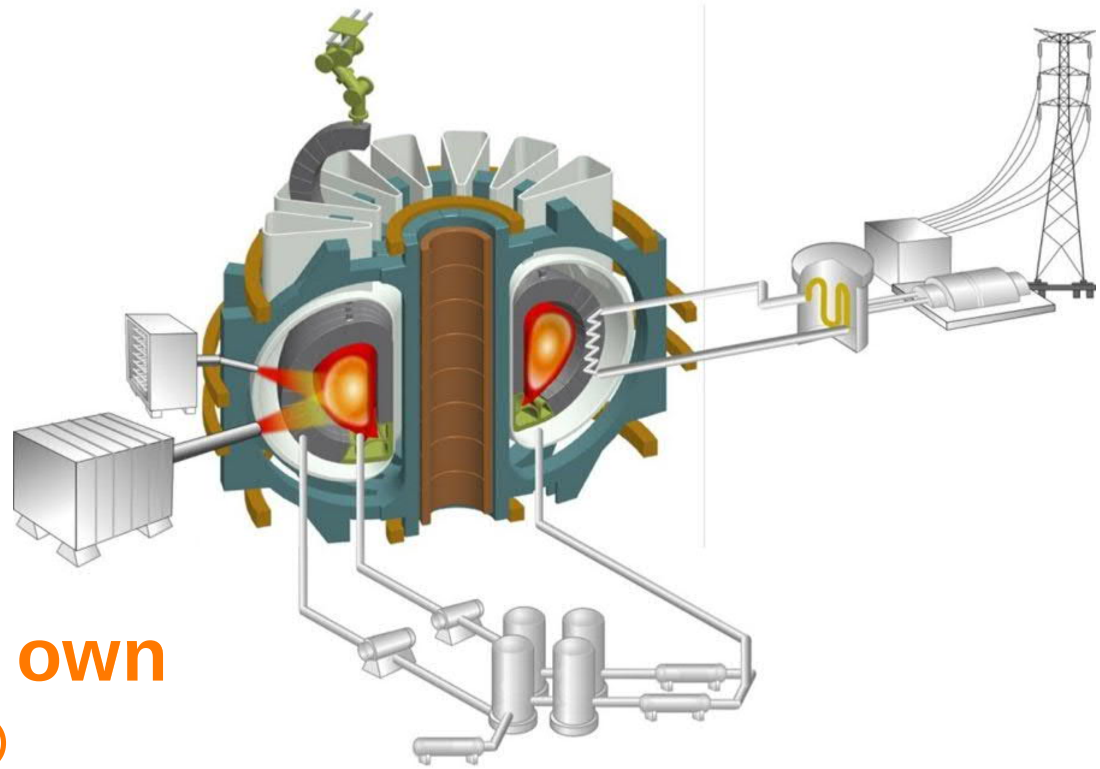
- Real-time control of power exhaust (~100 MW)

- Real-time plasma burn control (e.g., 50-50 mix)

	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%)

Zohm et al., IAEA-FEC 2012

” Korea aims at completing a DEMO by 2037”



Also China has its own DEMO design(s) ☺

A ghost from the past… *stellarator* !

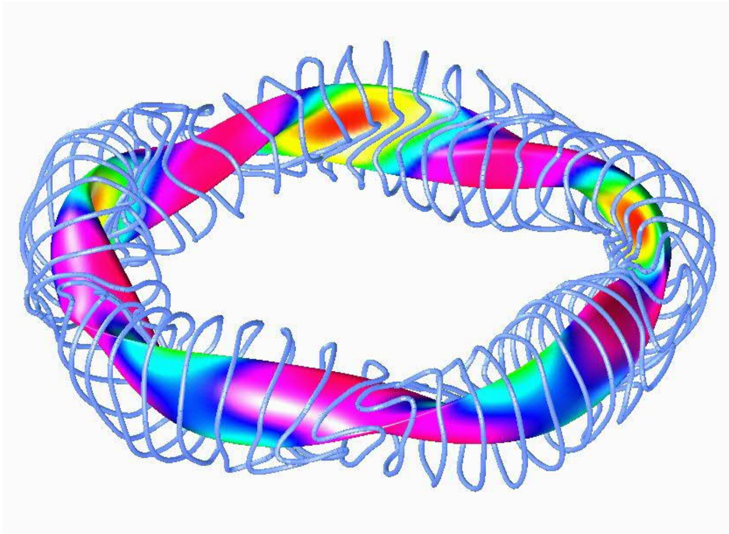
A stellarator -- Fusion with a twist …

The basic weakness of tokamak concept:

A pulsed device due to inductive current drive!!

How about creating the helical field 100% with external coils?

➔ A **stellarator** !



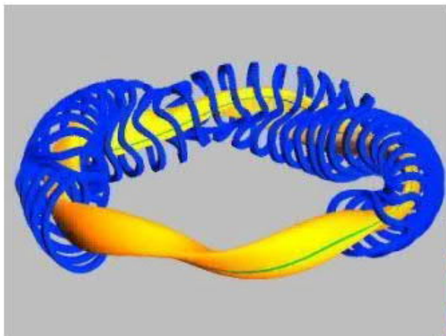
No plasma current ➔

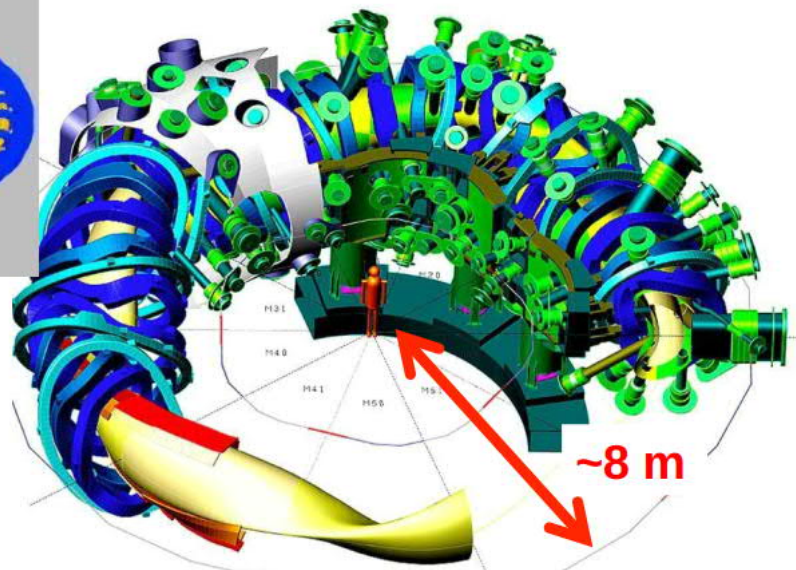
- Continuous operation!
- MHD quiescent plasma !

Wendelstein 7-X: world’s first super-conducting, optimized stellarator

- HELIAS (“pure stellarator”)
  ⇒ drift-optimized

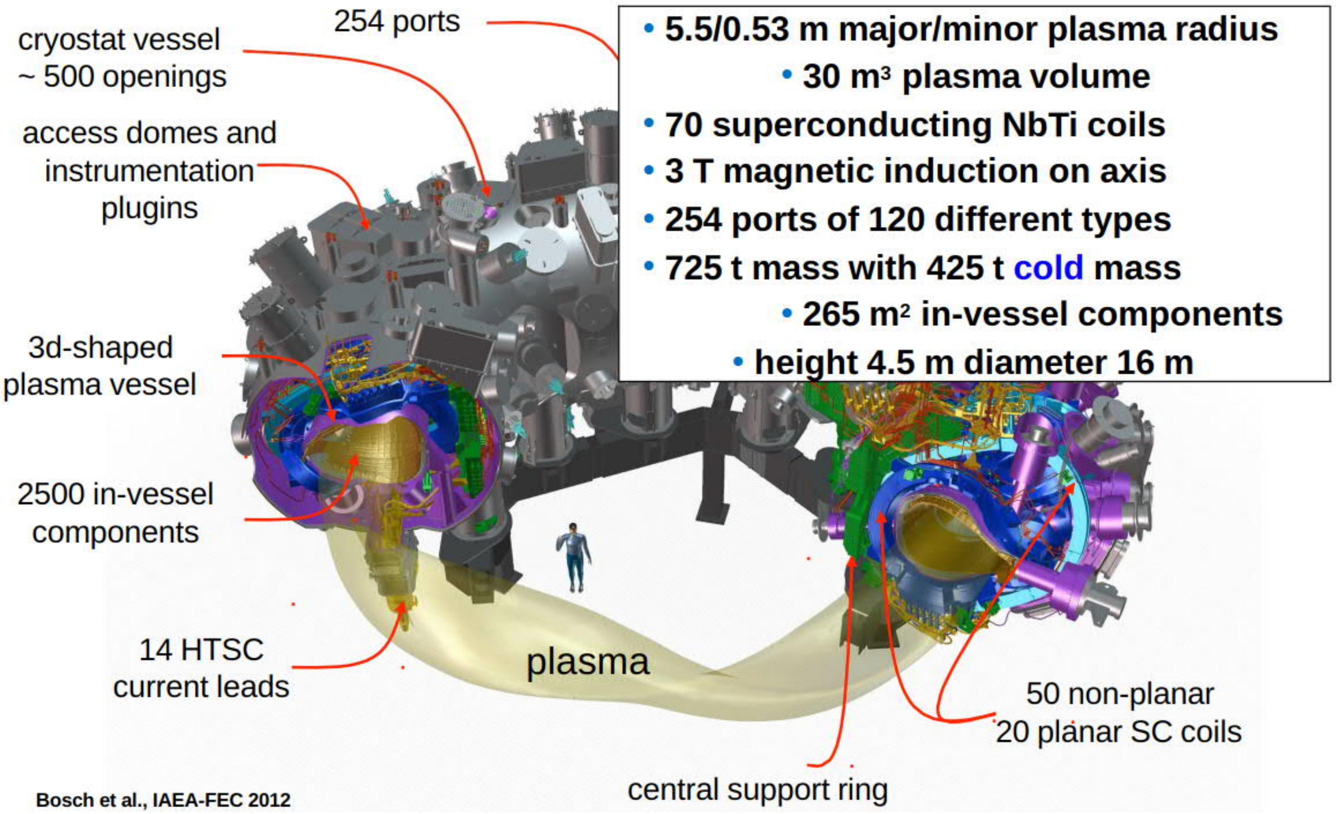
- R=5.5 m, a=0.52 m,
  V_{plasma}~30 m^{-3}
  (vs. JET: 3/1/100 and ITER 6/2/840)





- Fully cooled in-vessel components and island divertor

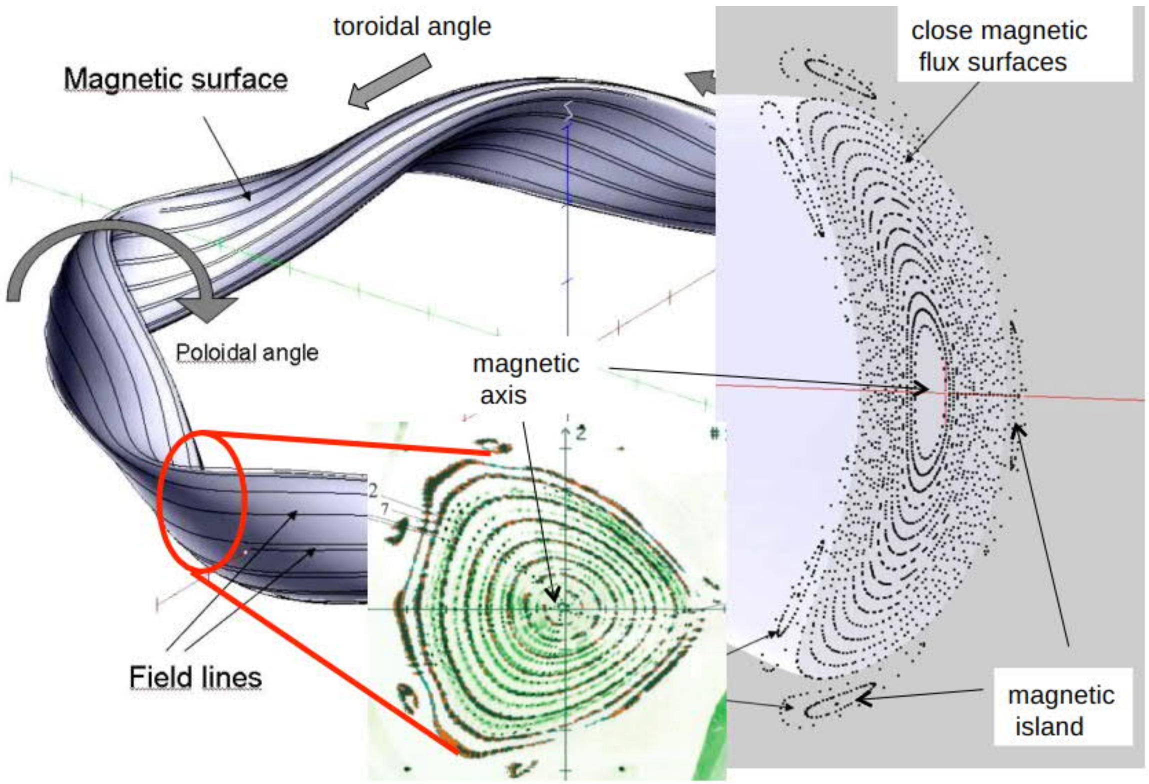
… but an engineer’s nightmare?



- 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

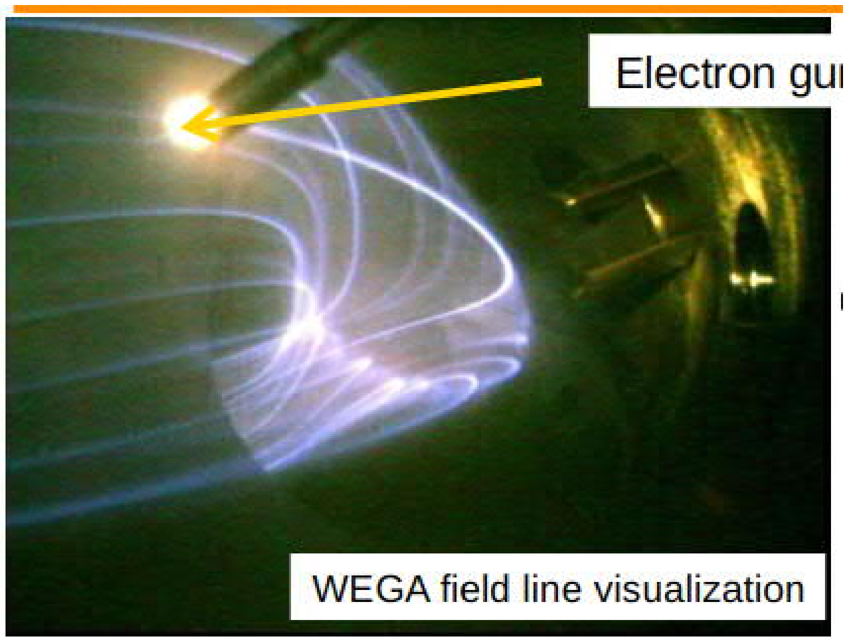
Bosch et al., IAEA-FEC 2012

Kiss symmetry goodbye …

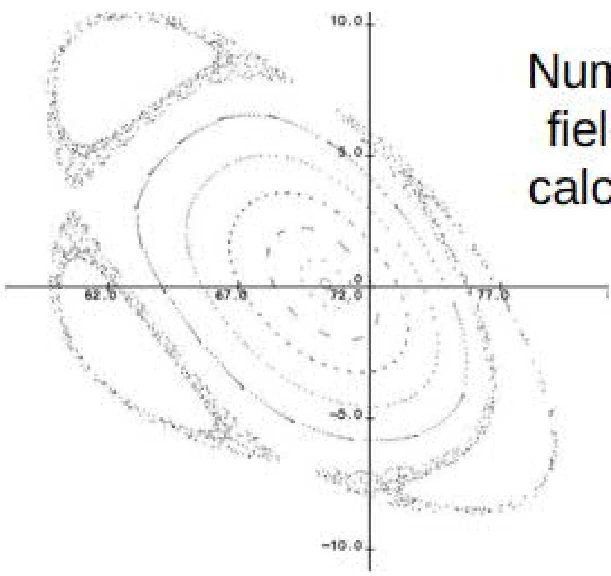


Vessel walls ’lick’ the plasma

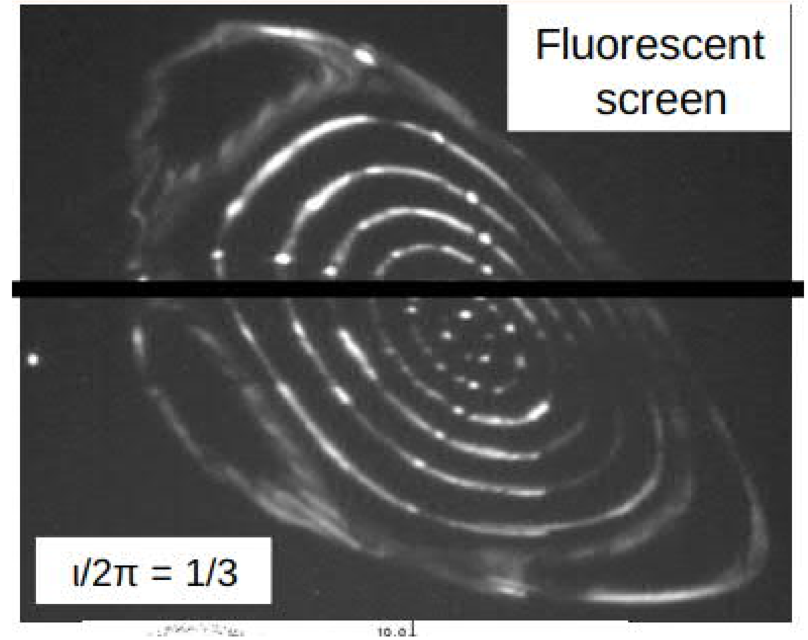
Stellarator too complicated for pen-n-paper
➔ optimized with super-computers …



… and verified by experiments !



Numerical field line calculation

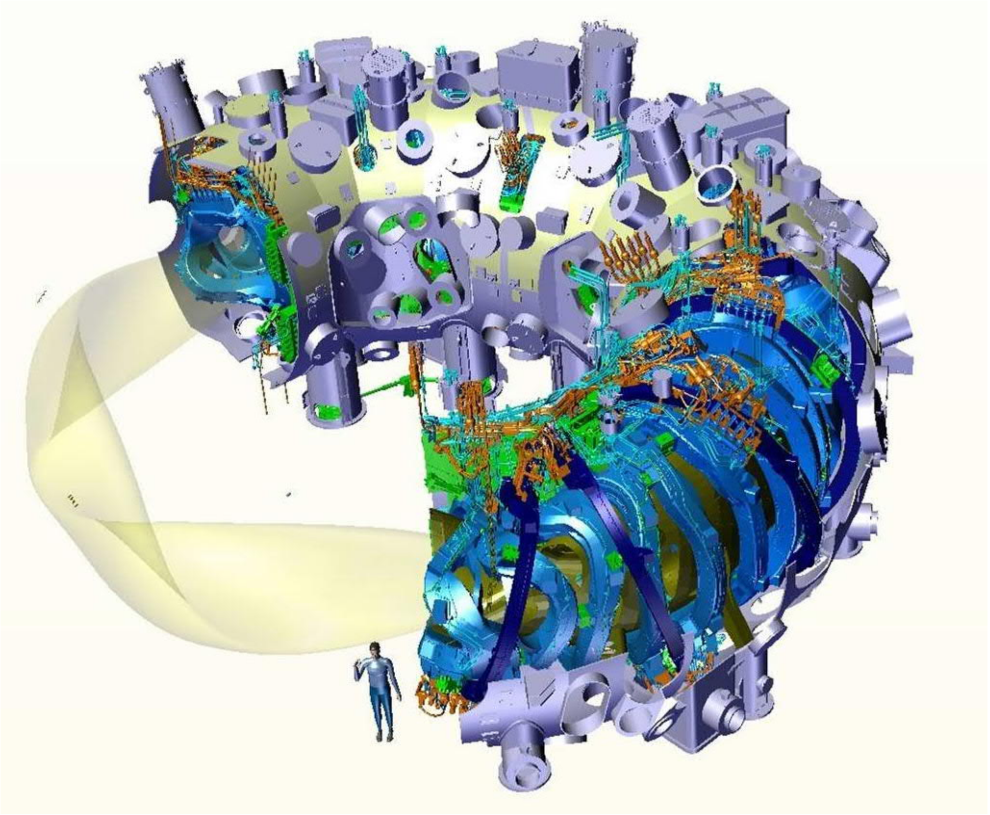


Electrons emitted parallel to calculated B in vacuum field without plasma ⇒ fluorescent projector and interaction with (Ar) background gas

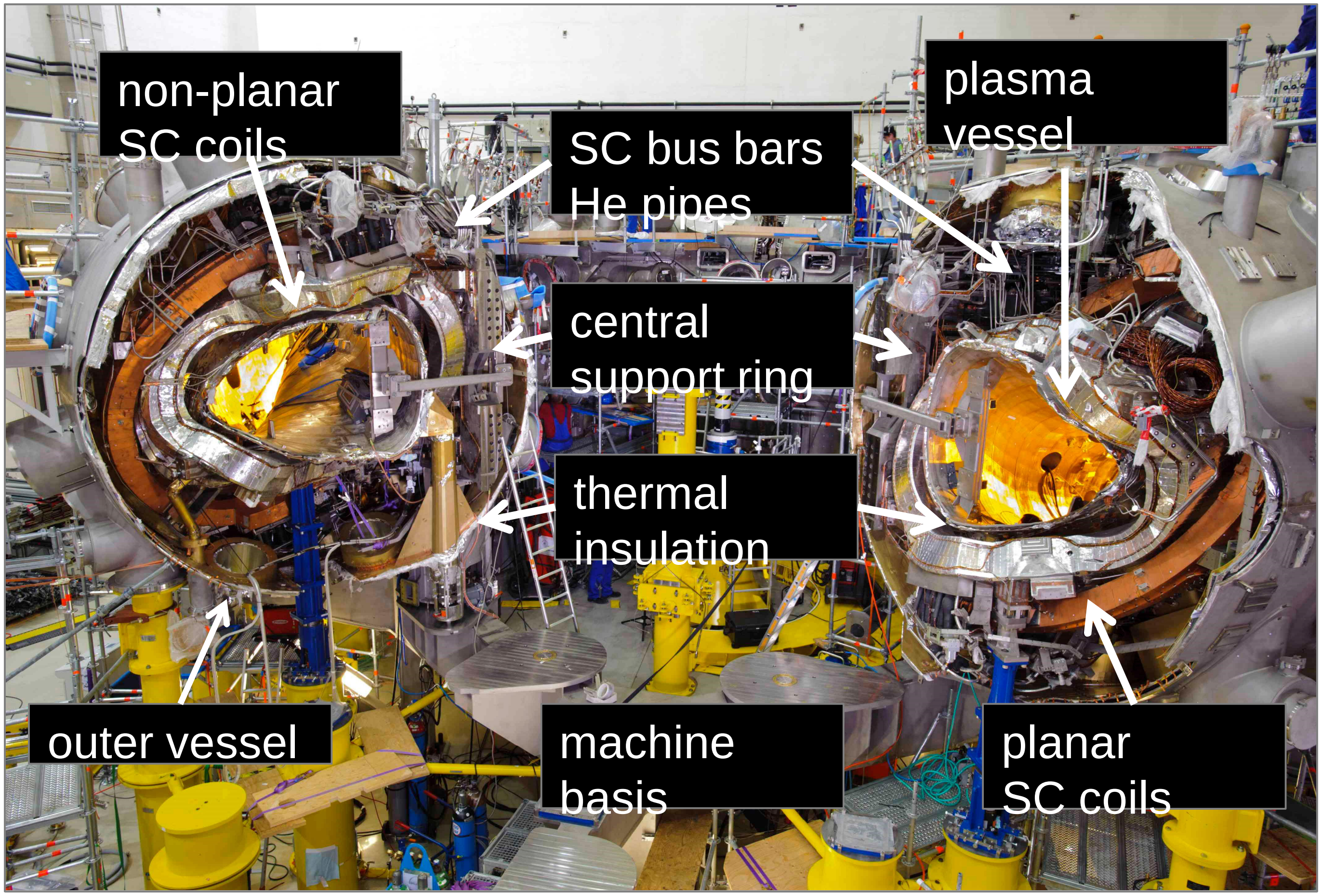
Wendelstein 7-X, technical data

major radius	5.5 m
minor radius	0.53 m
plasma volume	30 m^3
machine mass	725 t
cold mass	425 t

non-planar coils	50
planar coils	20
induction on axis	2.5 - 3 T
stored energy	600 MJ
heating power	15 - 30 MW
pulse length	30 min

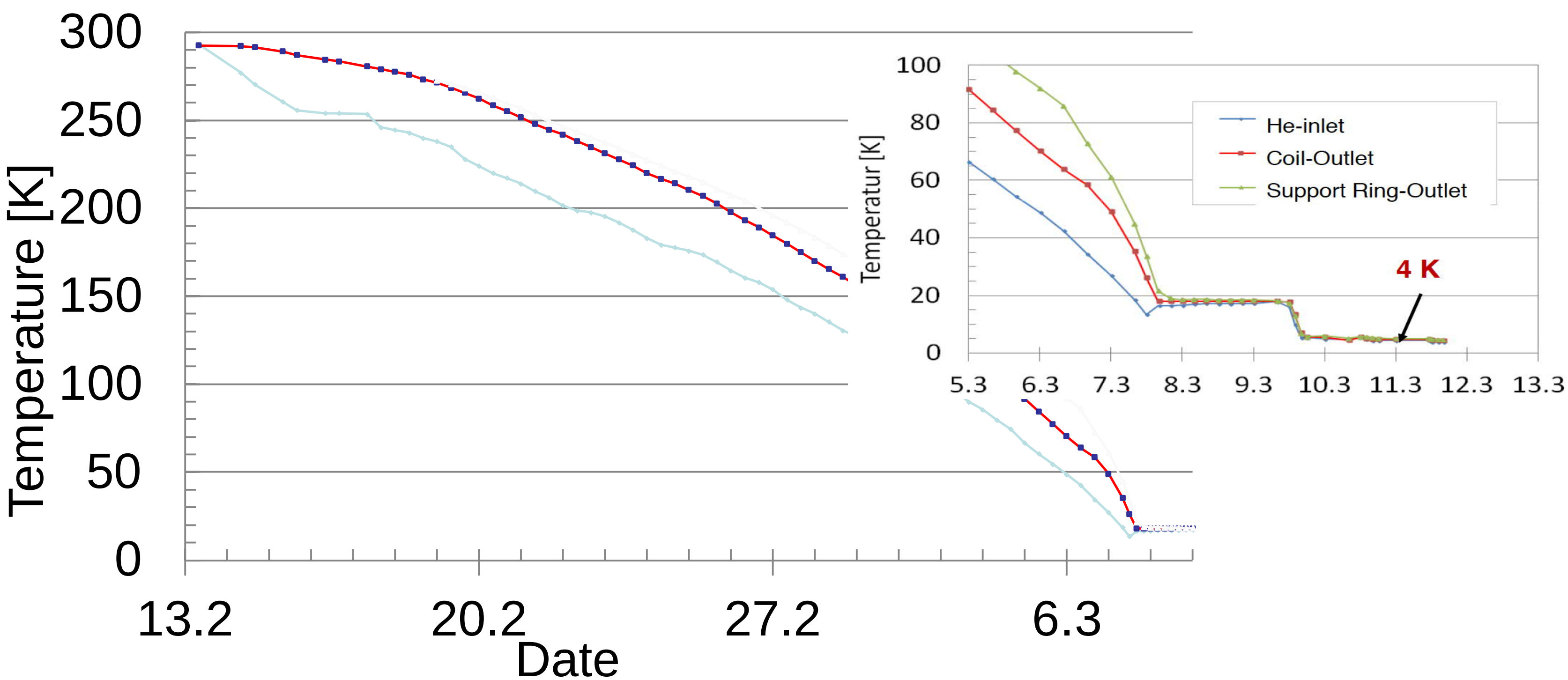


Under construction



Decoring the interior …

Commisioning 2015:
cooling the superconducting coils



First plasma shots 2016

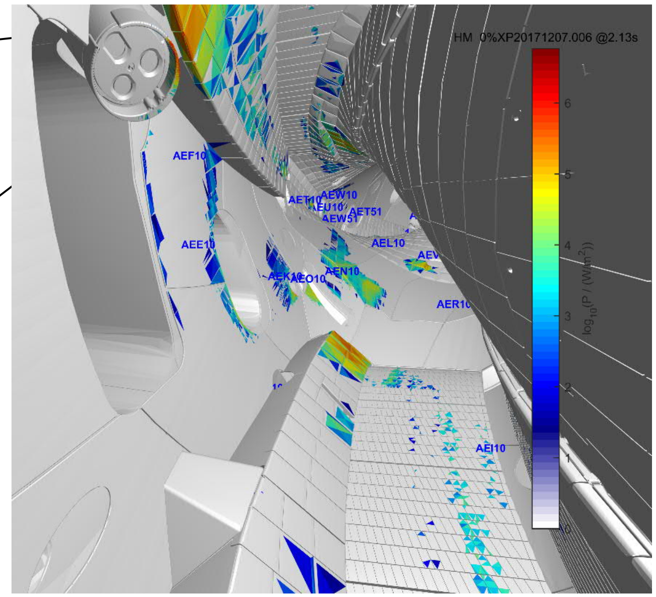
- Only electron heating
- Exceeded all expectations:
  - Electron temperature 7 keV
  - Ion temperature 1-2 keV

- Ultimate goal, when all bells and whistles installed:
- 2022 or so:
  - ~10 keV (ions),
  - Plasma duration ~30 minutes

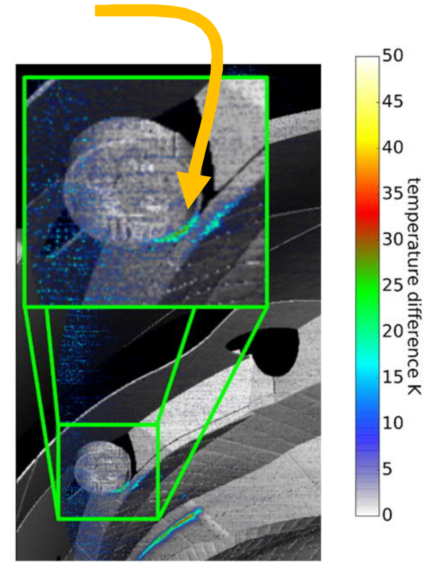
Wall design improved thanks to ASCOT simulations !

Fragile (sapphire) vacuum windows

ASCOT predicted excessive NBI power loads
➔
Protective collar installed before starting the beams

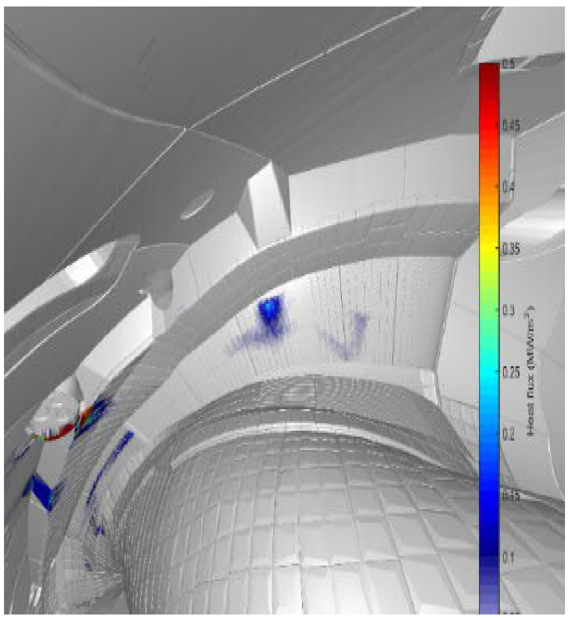


Wendelstein 7-X á l'ASCOT

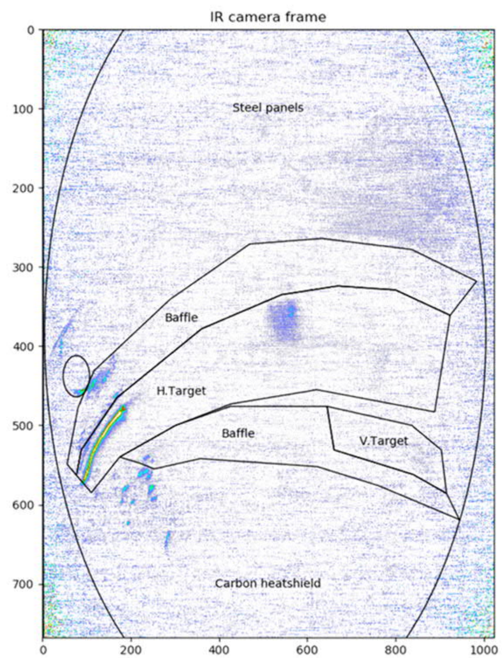


power loads in excess of 1.5MW/m^2 measured

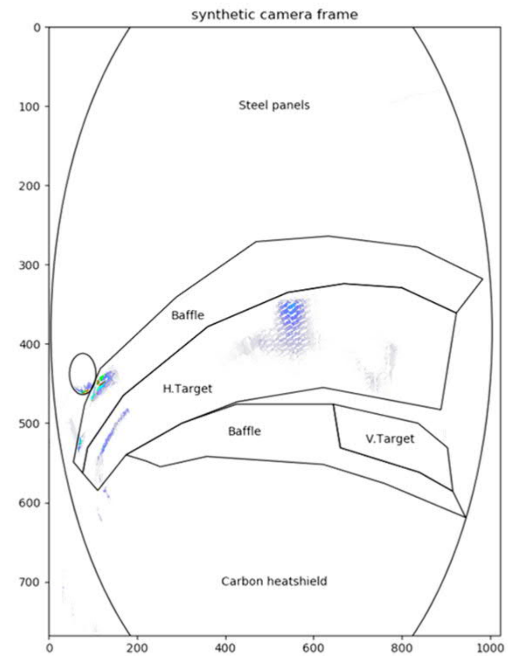
Experimental measurement reproduced by ASCOT !



ASCOT's view of W7-X intestines



InfraRed (IR) camera frame of the same place



ASCOT's synthetic IR camera frame

Today in the Ring …
Tokamak against Stellarator !

Tokamak

- Simple construction
- Good confinement
- Pulsed due to induction
- Plasma current ➔ temperamental plasma prone to (current-driven) instabilities

Stellarator

- Continuous operation
- Well behaving plasma
- Magnetic cage leaks
- Engineer's nightmare

So far tokamak leads the match with technical points, but W7-X can still do a knock-out …

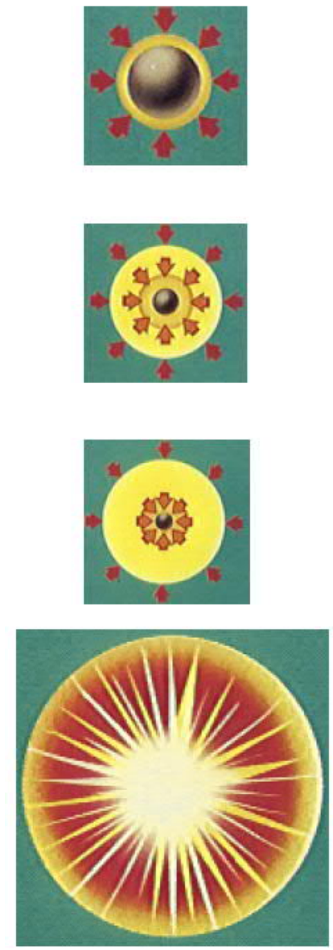
Rivals for traditional approaches …

Laser fusion? – small nuclear bombs…

- Laser fusion is most prominant of the so-called inertial confinement fusion (ICF) concepts
- In ICF, one could care less about confinement – only remaining confinement is via inertia of the electrons
- The world's greatest lasers are used to compress tiny, frozen DT-pellet to astronomical conditions
- Maybe not surprisingly, this research is funded by DOD … ;)
  - NIF = National Ignition Facility @ LLNL

Laser fusion has similar operating principles as rockets

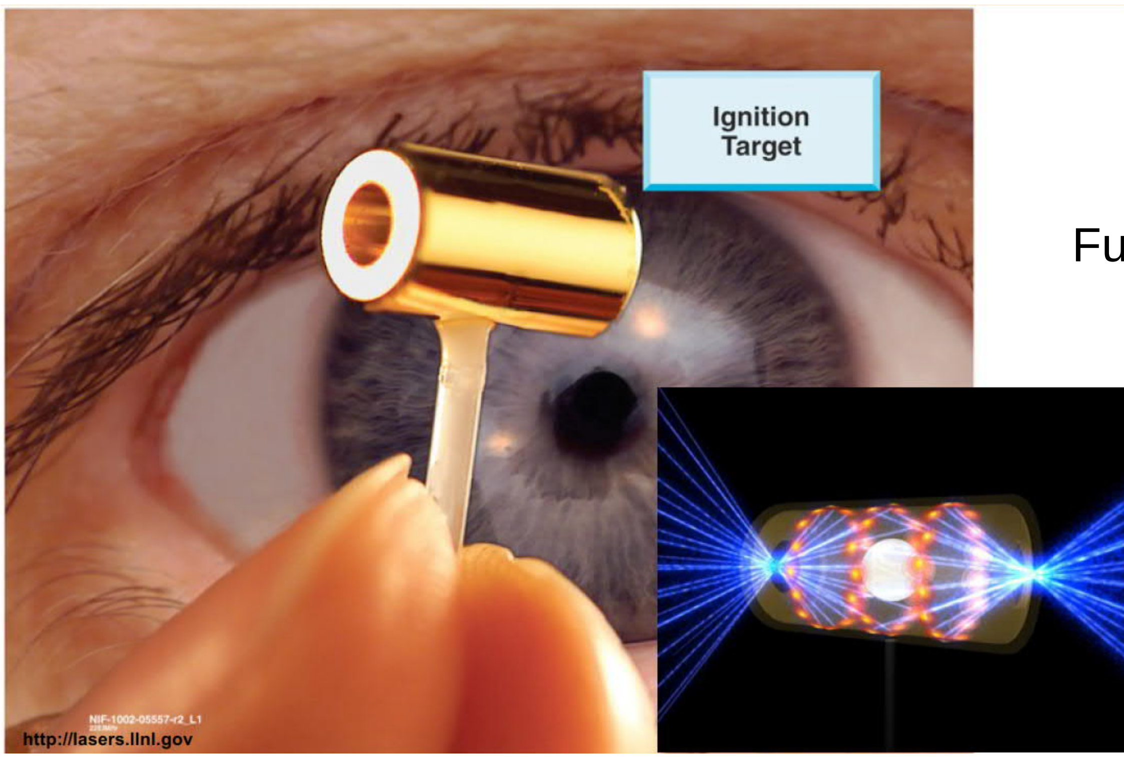
- Heat the surface of the capsule with radiation
- The fuel is compressed with surface ablation and rocket principle
- An enormous pressure is built in the core and the fuel ignites
- Followed by the burn phase



Lawson criterion reaches new heights

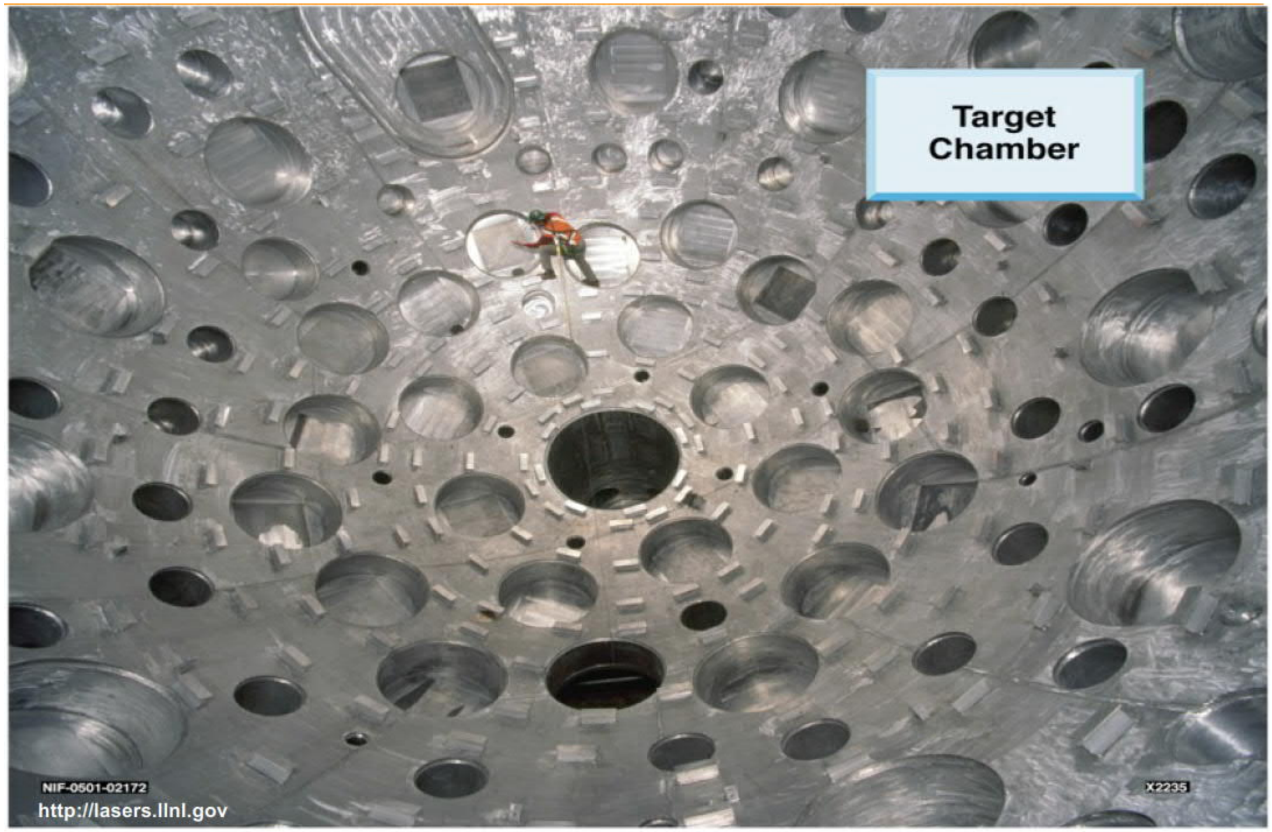
- Lawson criterion: $n\tau_E \approx 10^{20}$ m^{-3} s
- Magnetic confinement fusion
  – Density ≈ 10^{20} m^{-3}
  – Confinement time ≈ 1 (to 10) s ⇒ quasi steady state
- Inertial confinement fusion
  – Density ≈ 10^{31} m^{-3}
  – Confinement time ≈ 10 ps (10^{-11} s) ⇒ pulsed

Laser fusion -- tiny hydrogen bomb…



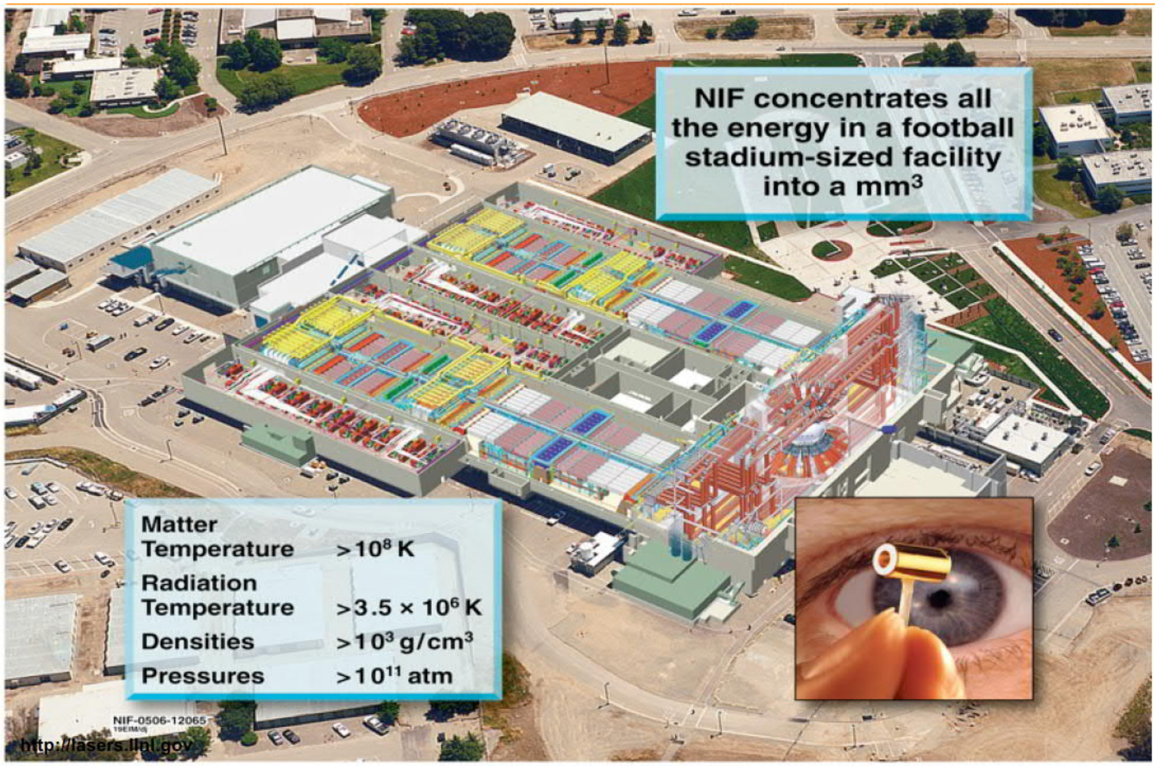
Fuel capsule’s size < cm

Target chamber is a little larger to compensate



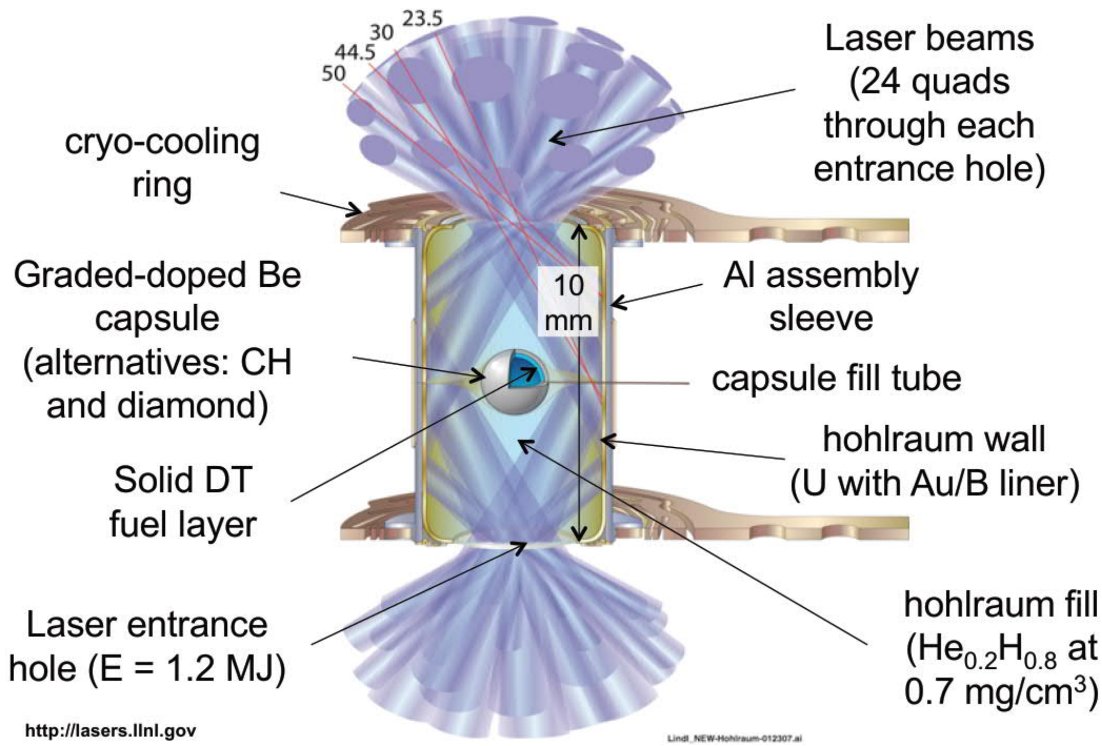
The NIF chamber has the radius of 10 m and weighs 130 tons

The lasers take even more space …




NIF is
705,000
square feet
DOLPHINS
49ers
PATRIOTS
MIAMI
SAN FRANCISCO
NEW ENGLAND
NIF-0705-11159 L29
http://lasers.llnl.gov

Very high-tech capsule



Results?

- Vielä viime vuonna ajattelin, että hohhoijaa, mutta sitten ….
- Physics Today 17.8.2021: ”A tiny pellet of deuterium and tritium released more energy than it absorbed from the National Ignition Facility’s bank of 192 lasers.”
  - 1.3MJ fuusioenergiaa vapautui. Edellinen ennätys oli 170kJ...
  - Hetkellinen teho 1016 W !!!
- Jos tämä tapahtuisi tokamakissa, sitä kutsuttaisiin break-eveniksi.
  - Miksikähän ei tässä tapauksessa? ;)

Yllättäin Nature vaikuttaa populistisemmalta kuin Physics Today:

” “… by generating more than 10 quadrillion watts of fusion power for a fraction of a second — roughly 700 times the generating capacity of the entire US electrical grid at any given moment”

https://physicstoday.scitation.org/do/10.1063/PT.6.2.20210817a/full/

https://www.nature.com/articles/d41586-021-02338-4

In addition, all kinds of private entrepreneurs

- Tokamak Energy Ltd (ST with HTS magnets)
  - https://www.tokamakenergy.co.uk
- LIFE (fusion-fission-hybrid)
- Tri-Alpha
- Lockheed-Martin
- … you name it

Newest new: USA wants regain lead … SPARC !!

https://www.psfc.mit.edu/sparc

- Compact, high-field, DT burning tokamak at MIT
- Confine a plasma with net fusion energy
- Aggressive schedule: working in 15 years
- High-risk, high-gain project
- VERY similar to European TE Ltd but with more hype