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
- ITER+DEMO(s)
- Stellarator
- ICF

# Fusion energy rules!

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?

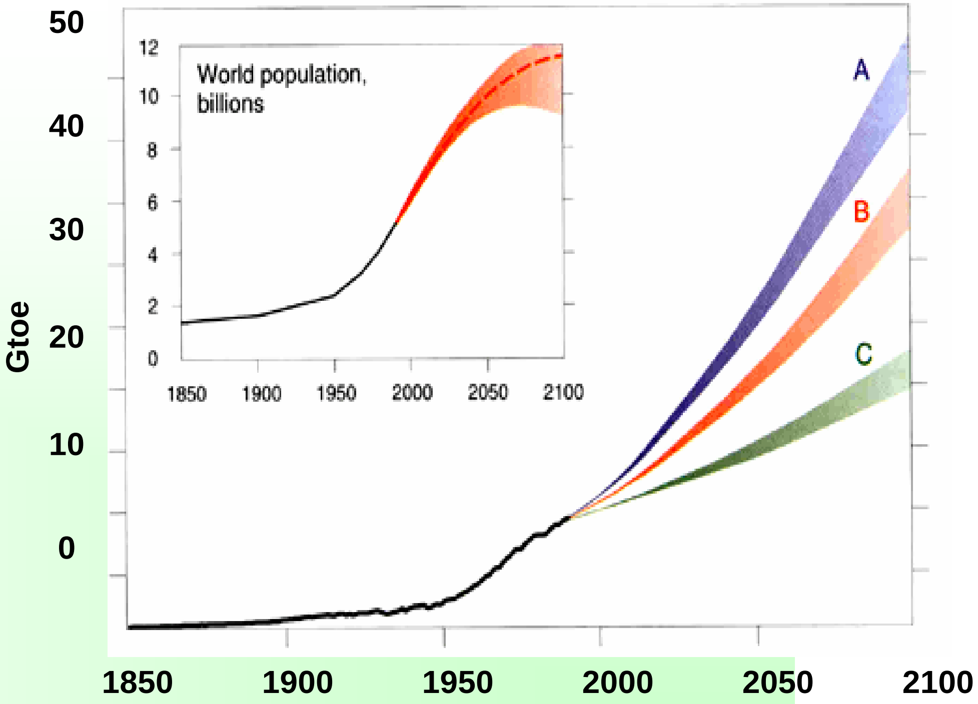
# Would be badly needed ...

# 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 ($H_2O$, bio, solar, wind)
- fission ($^{238}U$, Th)
- fusion

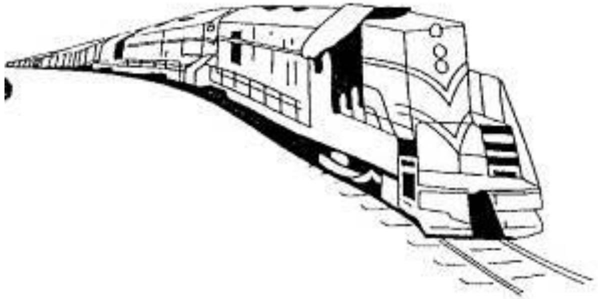


# Energy density:
## Fuel needed by a 1000 MWe power plant per year

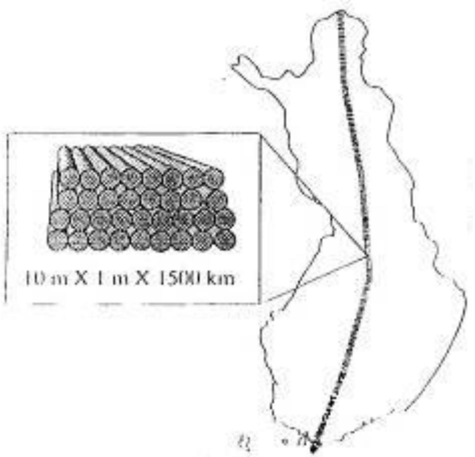
Nuclear power plant
30 tons of enriched Uranium
(two truck loads)

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,**

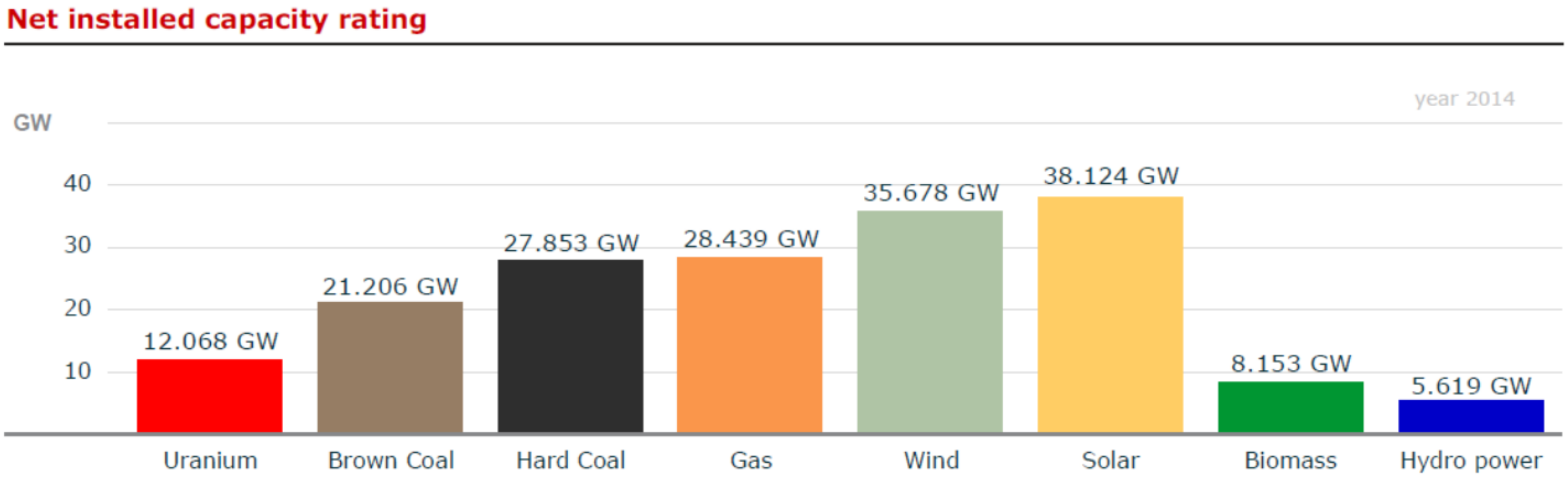
**or**

- **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***



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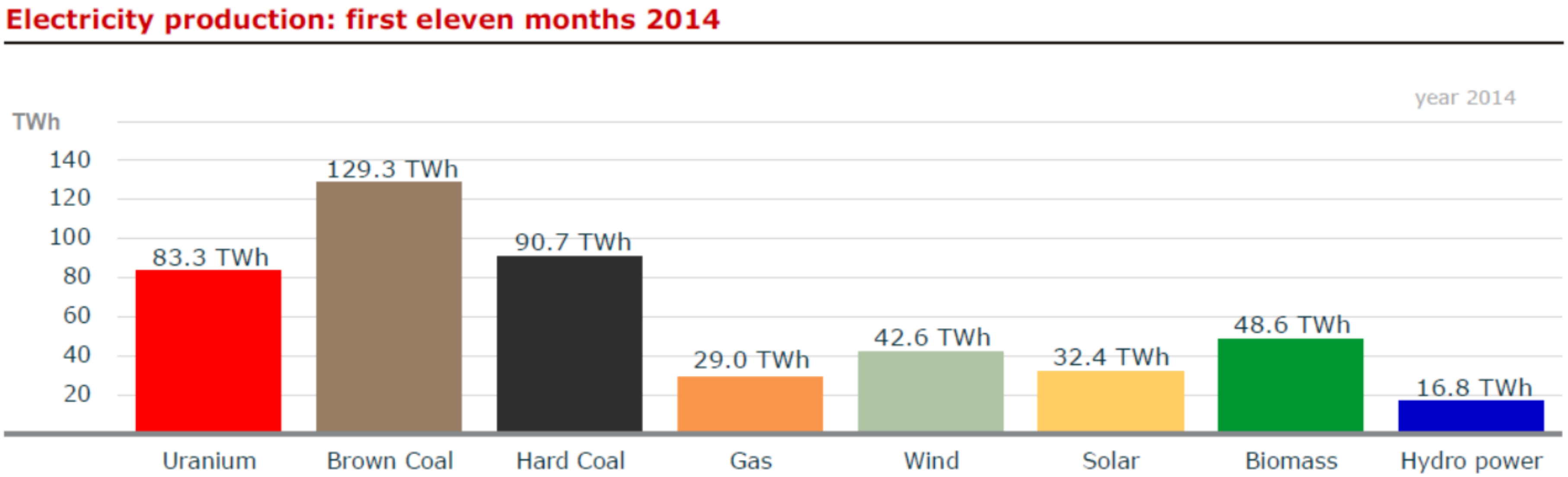
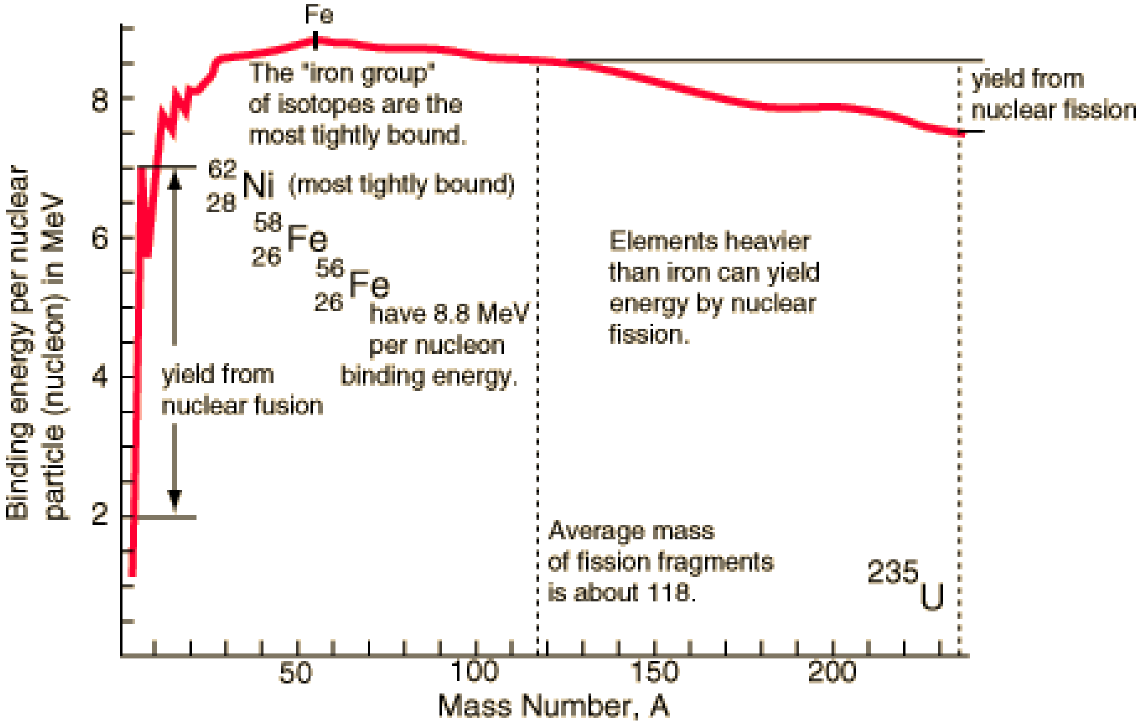


# From the energy gain point-of-view, fusion is *very* attractive…



# 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 (→ 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:

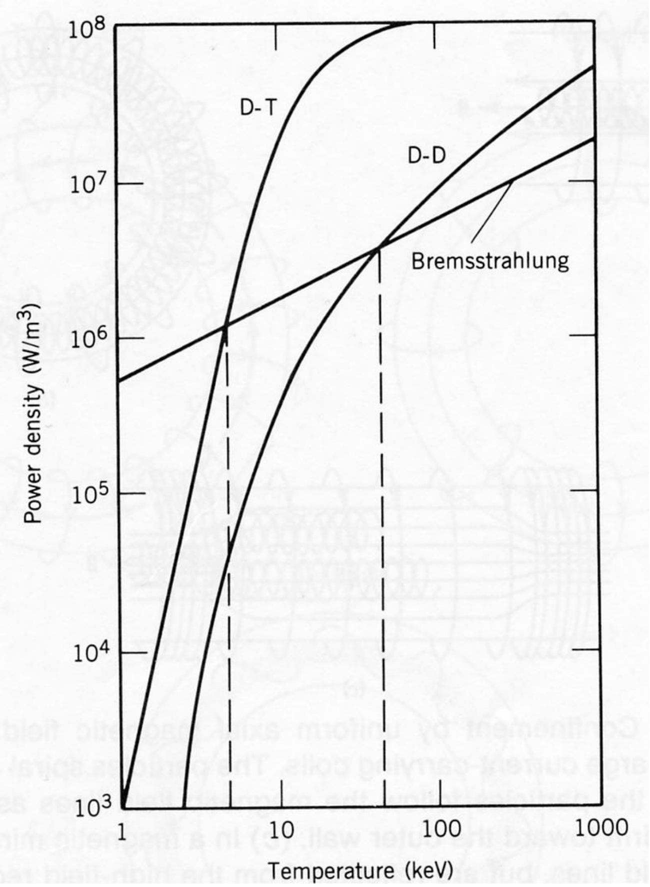
$$P_{in} = \eta P_{out} > P_{loss} \; ; \; \eta = \text{conversion efficiency}$$

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

$$\Rightarrow \eta P_{fus} > (1- \eta)P_{loss}$$

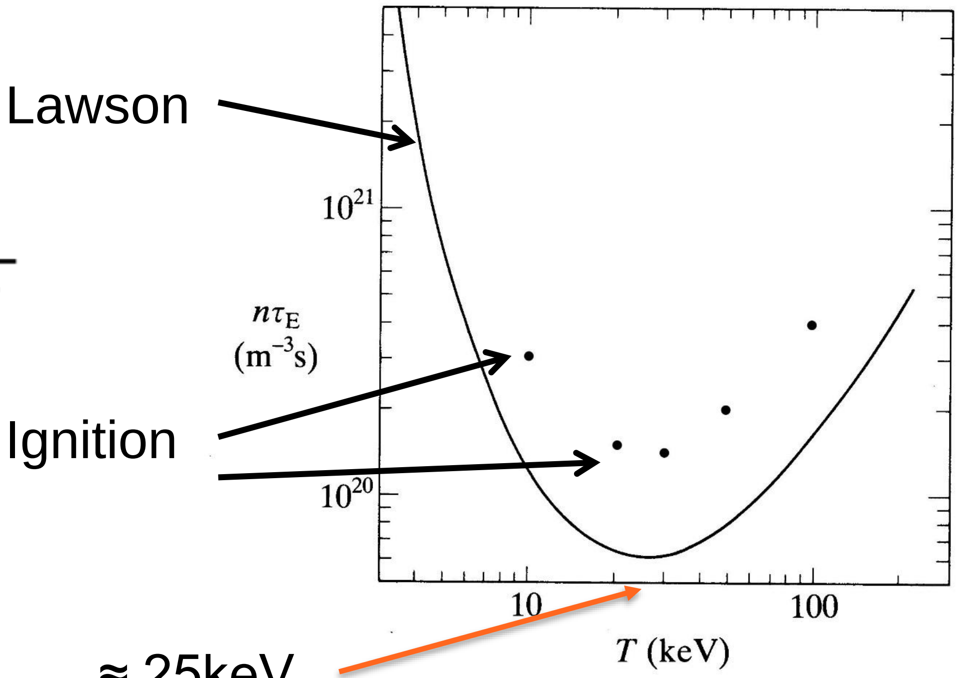
# Fighting for dominance

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



# ➔ Lawson criterion

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




$T_{optimal} \approx 25keV$

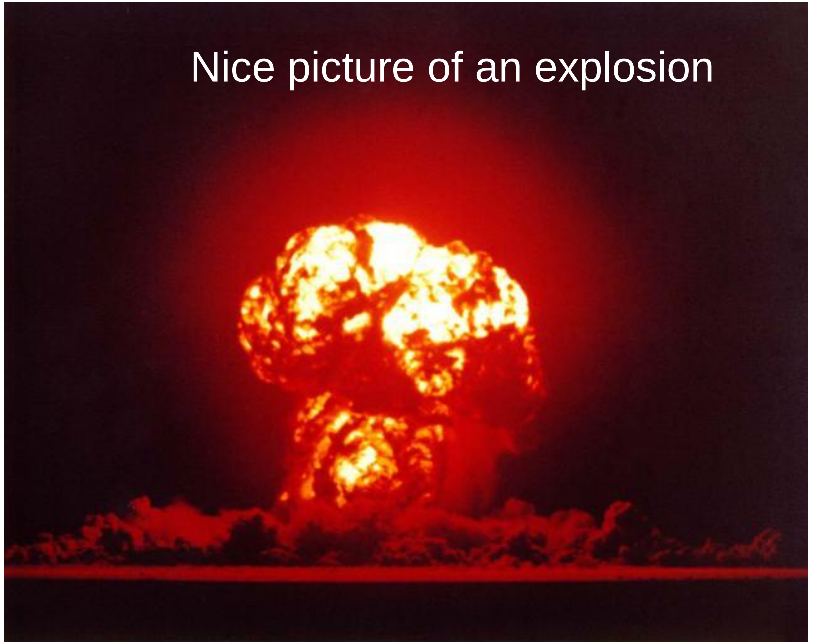
# Reaching the criteria, Part I: ICF

Maximize the pressure, nT

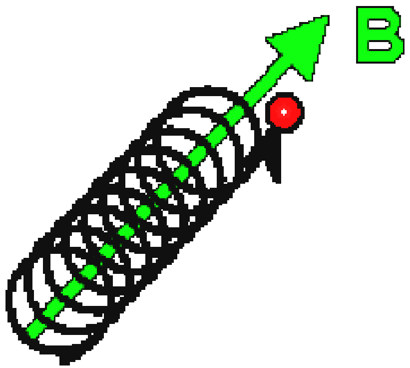
➔ 'inertial confinement fusion' = confinement only by inertia of particles

- 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 $\tau$



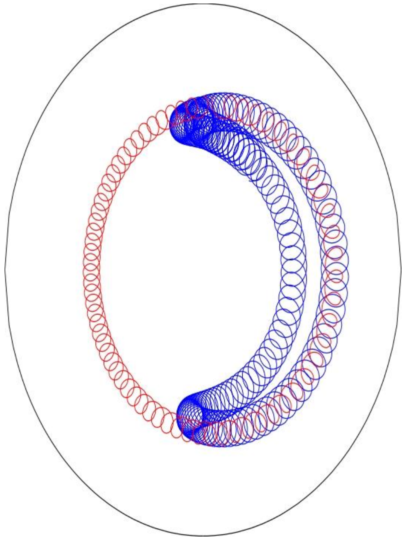

Charged particles glued to magnetic field lines !

… 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

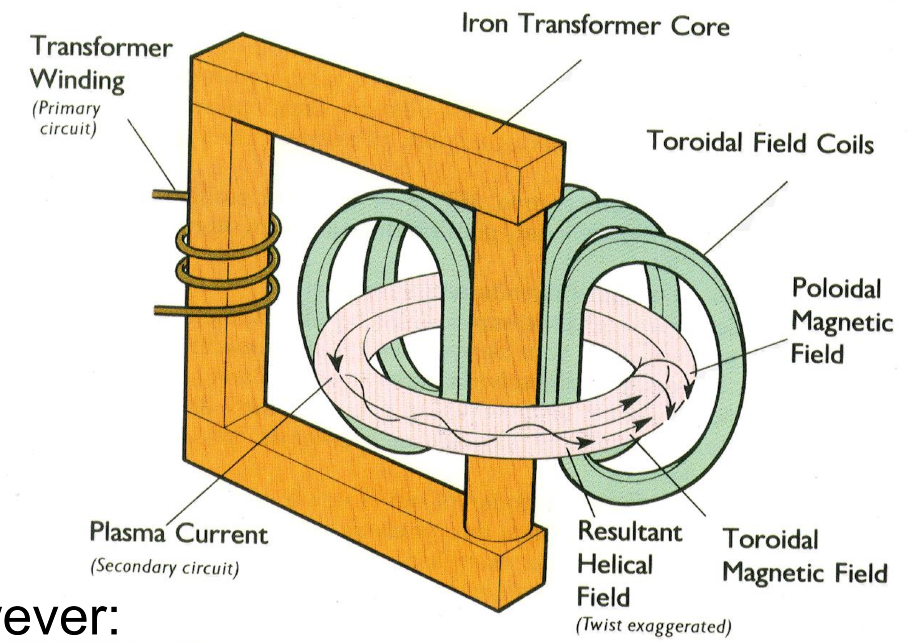
*toroidal'naya kamera v magnitnykh katushkakh — toroidal chamber in magnetic coils*

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
  - ➔ $\nabla$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:

$$\nabla p = \mathbf{j} \times \mathbf{B}$$

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

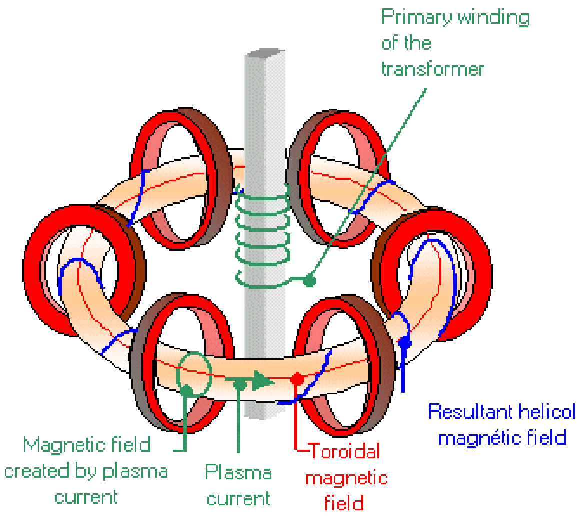
➔ Confining field = $\mathbf{B}_{pol}$ !!

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

*In both cases the end result is helical field lines*

# How is a fusion plasma created?

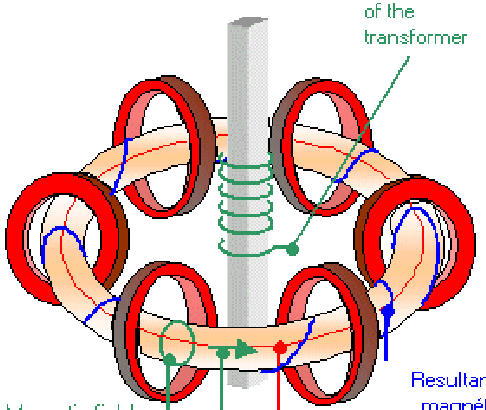
# Marching order




- 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!

# Marching order

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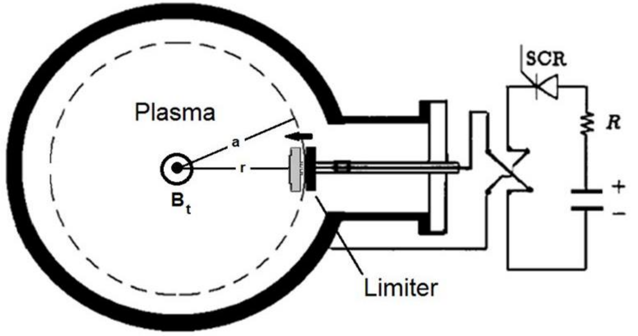
➔ helical field lines & plasma -- we are ready to go!

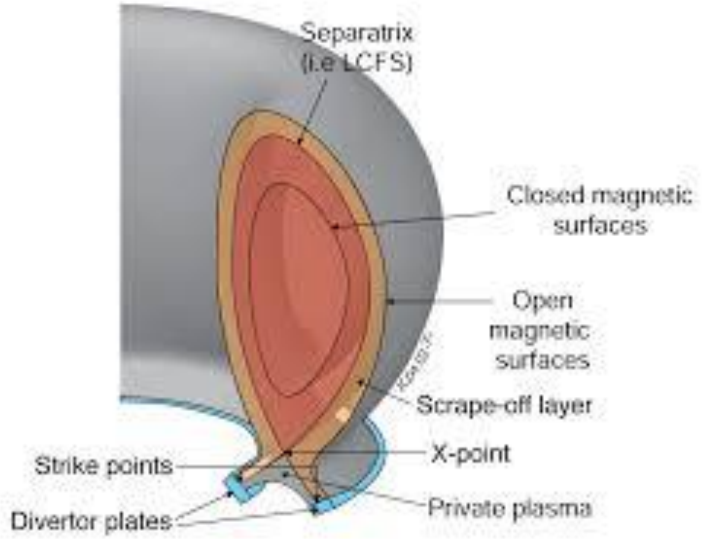
- If plasma heated further, H-mode (high confinement mode) appears
- H-mode vs. L-mode (low confinement mode) -> significantly improved performance
- Cost of H-mode, the ELMs (Edge localised mode)

# 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



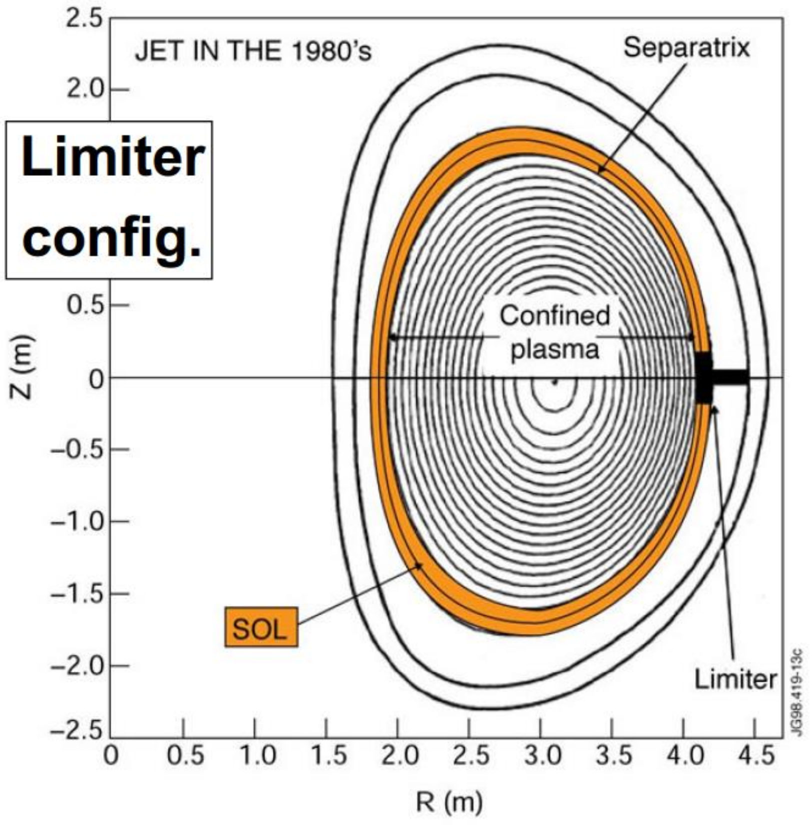
# Example: JET tokamak before …

Notice: plasma cross section is not circular

Why does it make sense to elongate vertically?

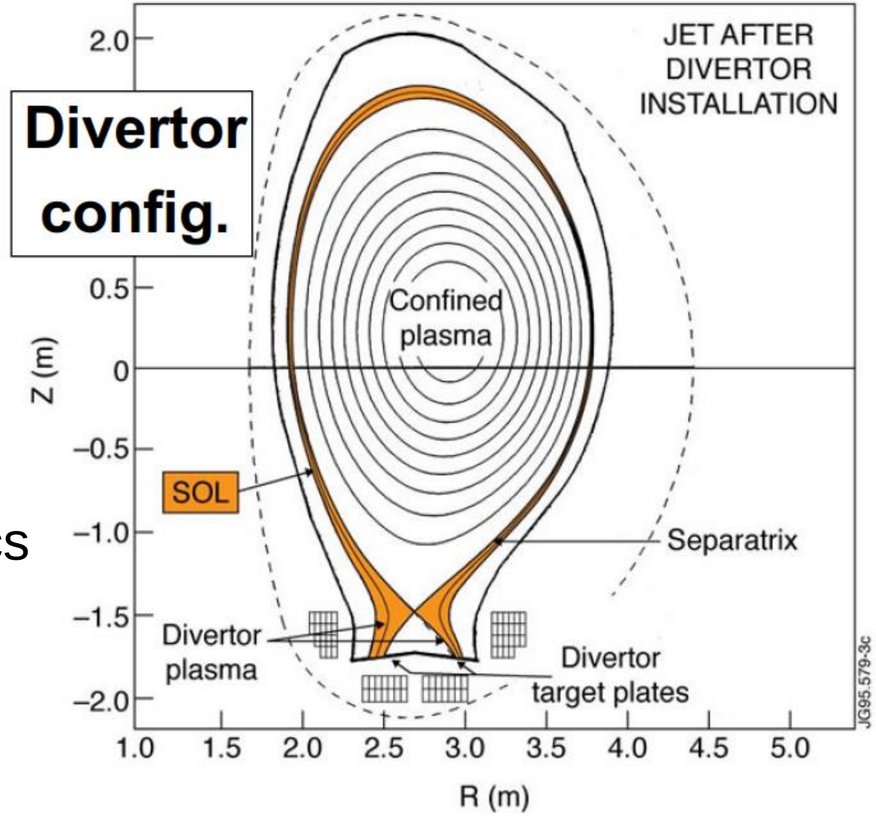
Nowadays plasmas are *triangular*

New concept:
*Scrape-off layer, SOL*



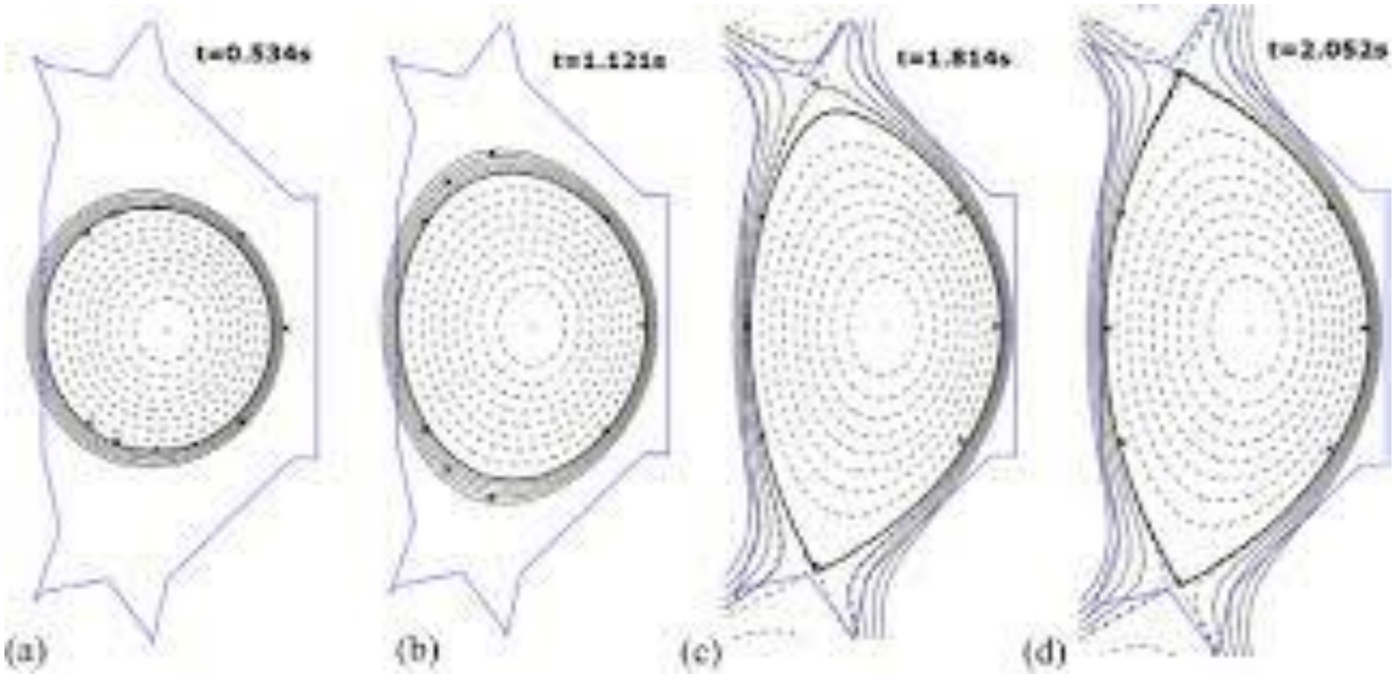
# Example: JET tokamak before and now

- In 1997:
  - DT plasma
  - 16 MW Peak
  - Carbon wall
  - Poor diagnostics



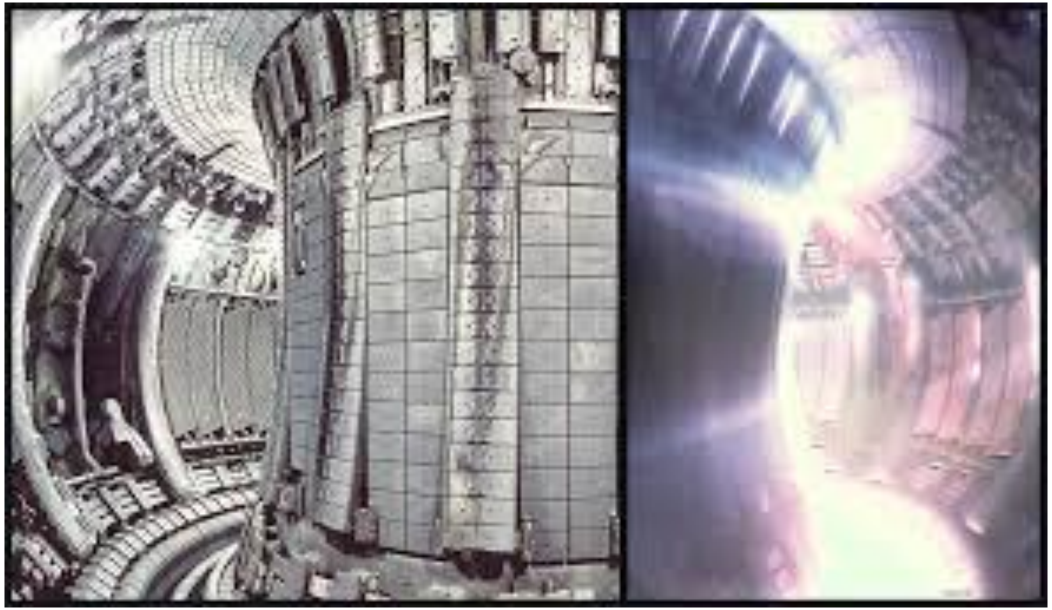

- In 2021:
  - DT plasma
  - 56MJ in 5s
  - B/W wall
  - Well diagnosed

# Plasma still starts up at the limiter

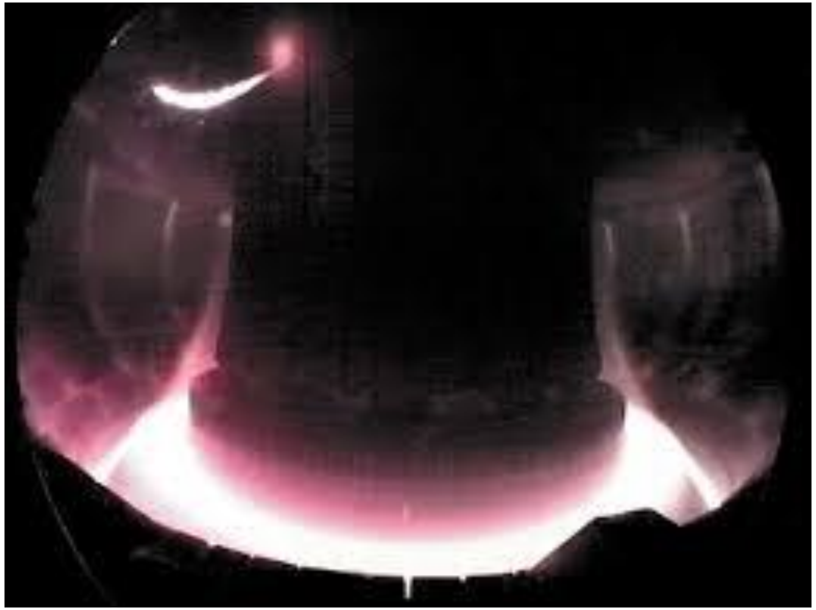



Q.P. Yuan et al., *Plasma current, position and shape feedback control on EAST*
Nuclear Fusion, Volume 53, Number 4

# How does a tokamak plasma look like?



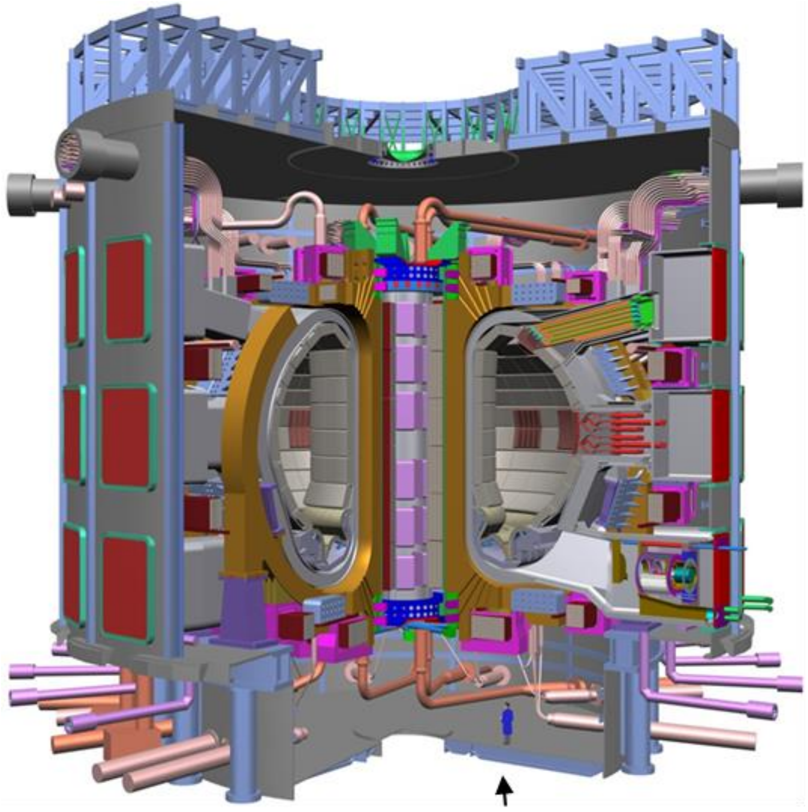
JET tokamak
CCFE
Abingdon, U.K.



ASDEX Upgrade
Max Planck institute
Garching, Germany

# How is a plasma heated?

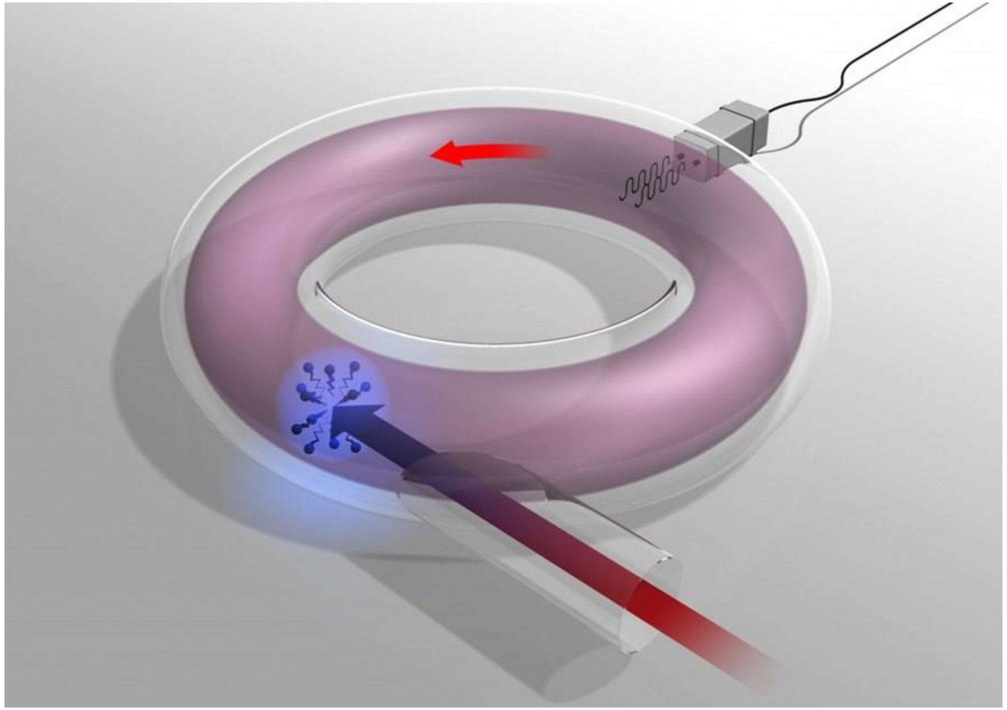
# ITER – world's first fusion reactor



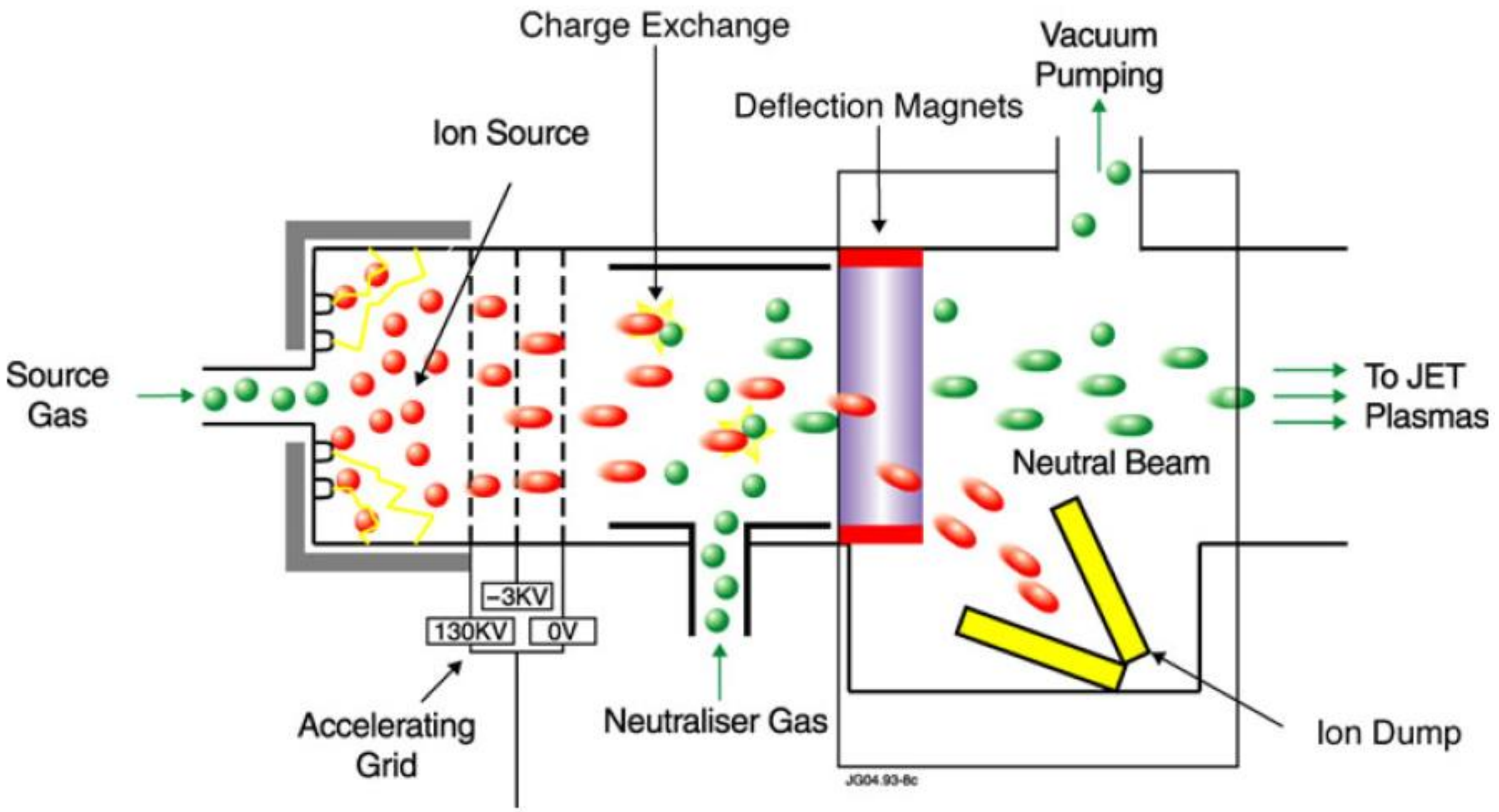
Yleismies Jantunen rööreja tsiikaamassa

Total heating power **50 MW …**

# Heating methods:
# *neutral beams and RF waves*



# Working principle of a neutral beam



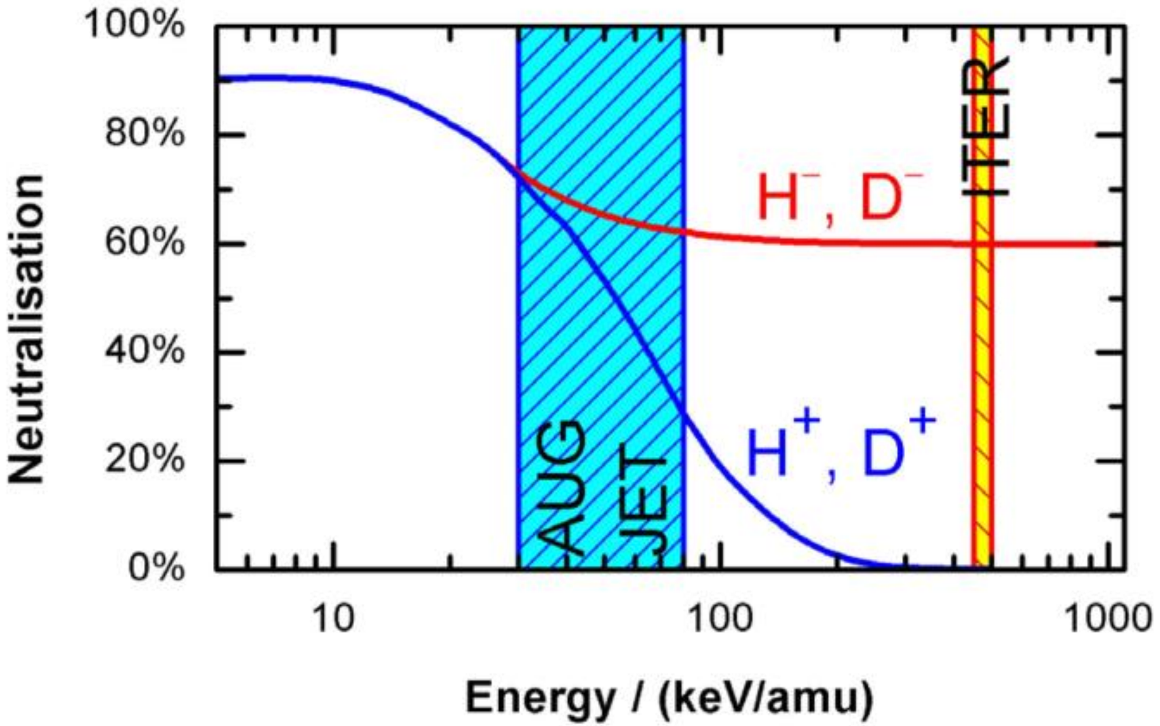
# What are *negative* neutral beams? And why?

The beam energy determines

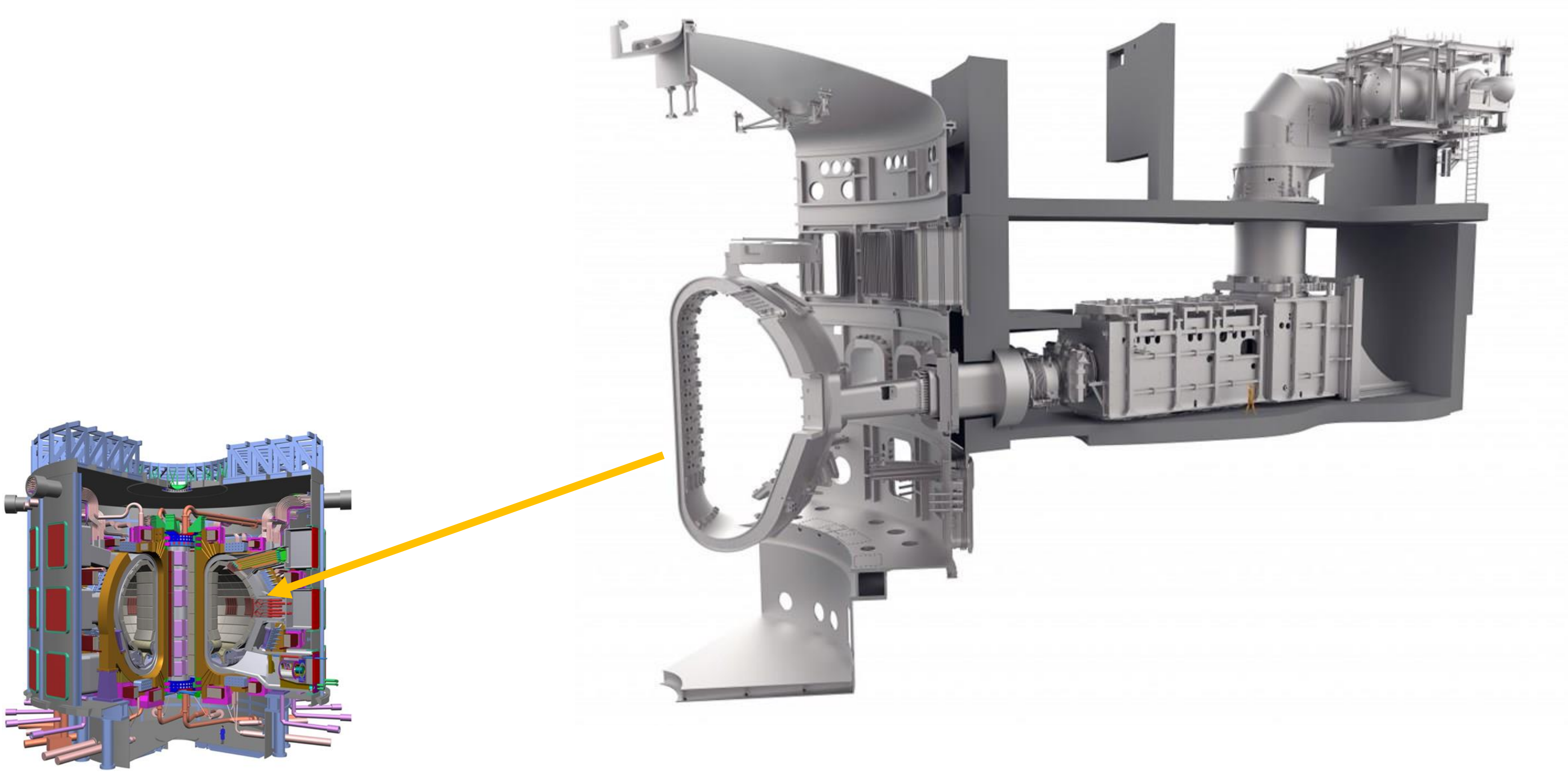
- Deposition depth in the plasma
- The amount of *shine-through*

Also the direction of the beam affects both deposition and shinethrough

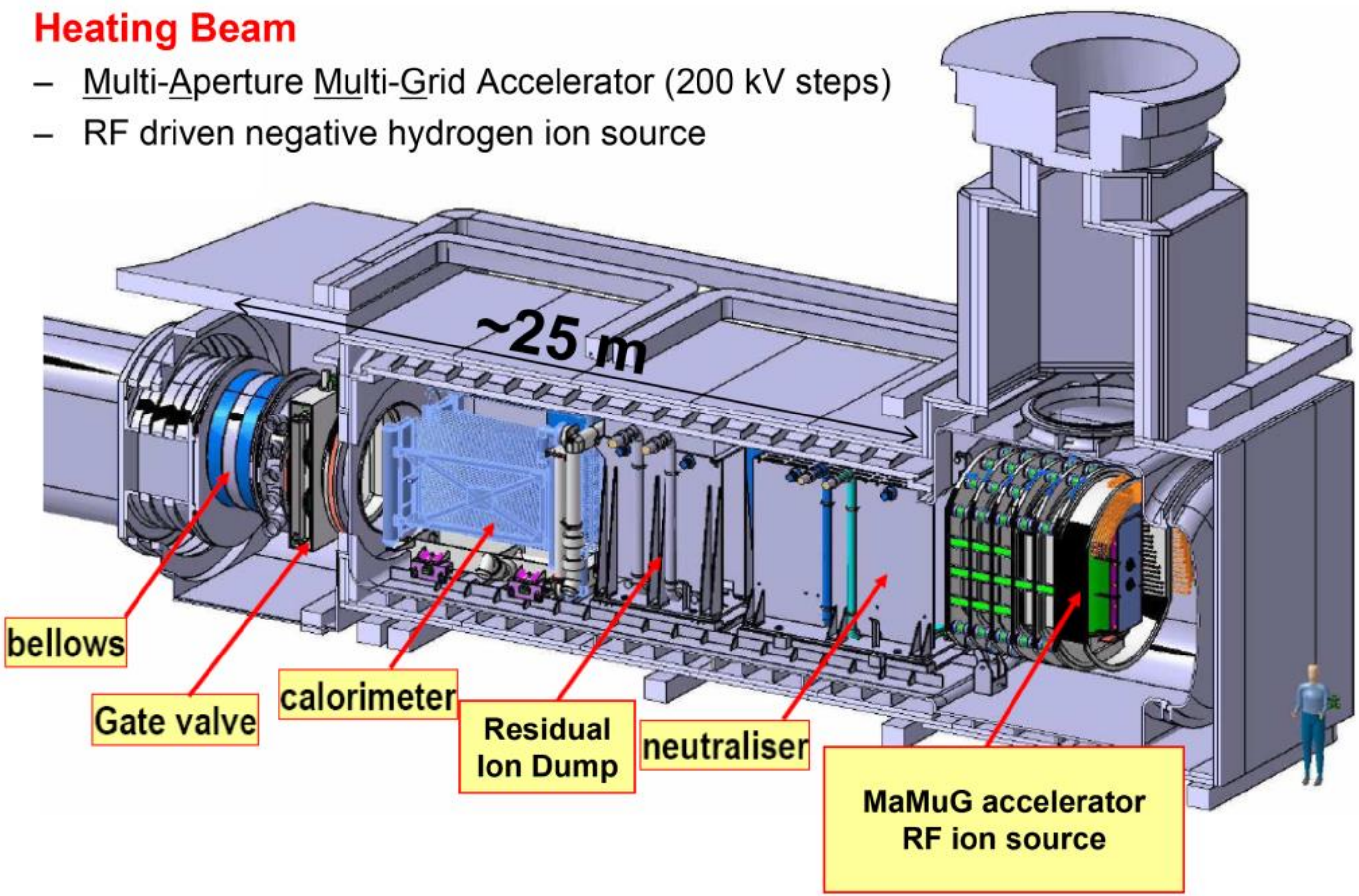
$E_{NBI} > 20T_e$ ➔ fast ions born from beams slow down predominantly on *electrons*



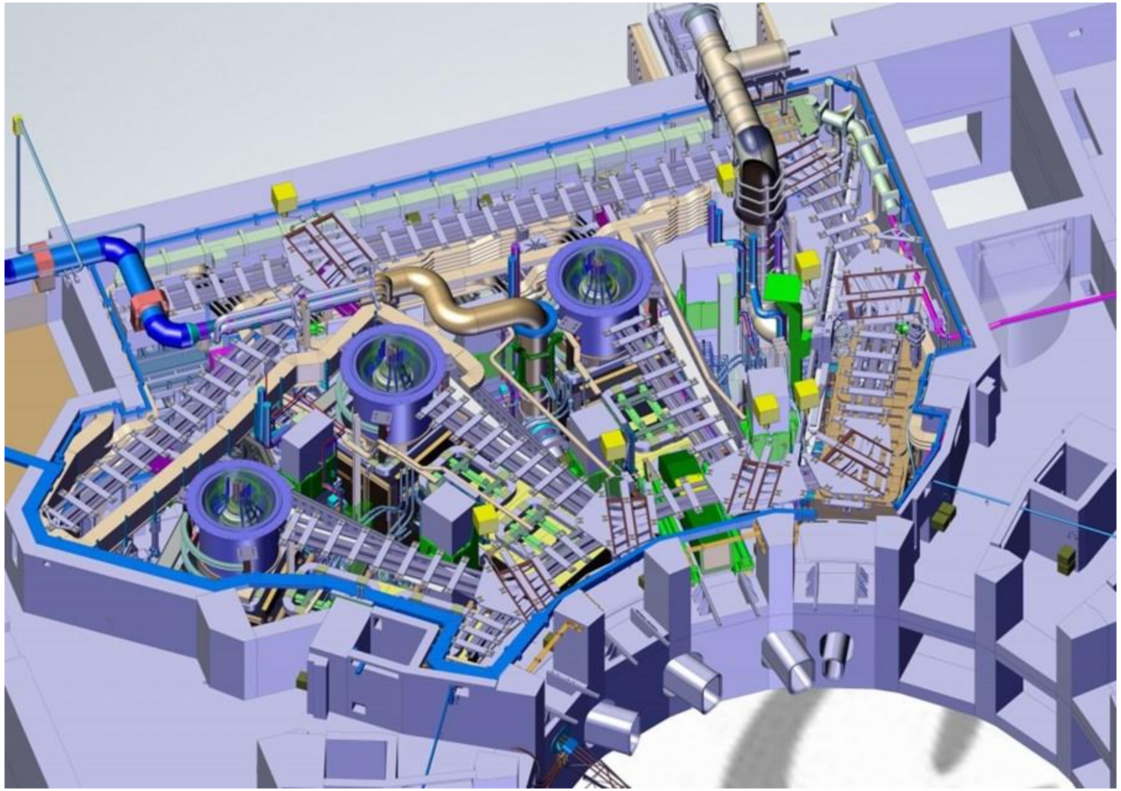
# ITER NBI – notice the size …



# Beam box


Heating Beam
– Multi-Aperture Multi-Grid Accelerator (200 kV steps)
– RF driven negative hydrogen ion source
~25 m
bellows
Gate valve
calorimeter
Residual Ion Dump
neutraliser
MaMuG accelerator RF ion source

# ITER: 3 injectors, 3 directions



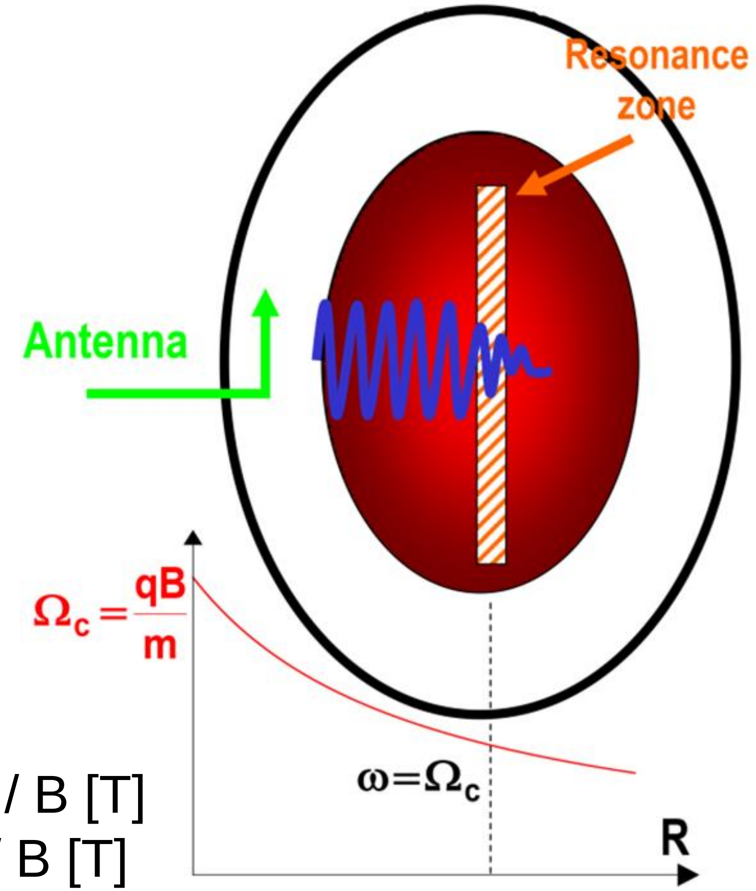
# NBIs around the world …

| 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:

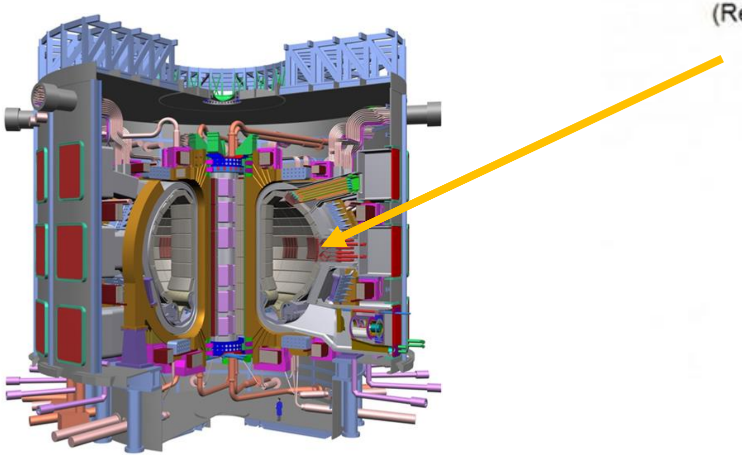
- Excite an RF wave at frequency ω close to plasma edge
- Wave propagates in plasma (non-trivial)
- Wave gets absorbed at a resonance layer where $\omega = \Omega_e$ or $\Omega_i$
- Particles accelerated by the wave transfer the energy to bulk plasma thus heating it up

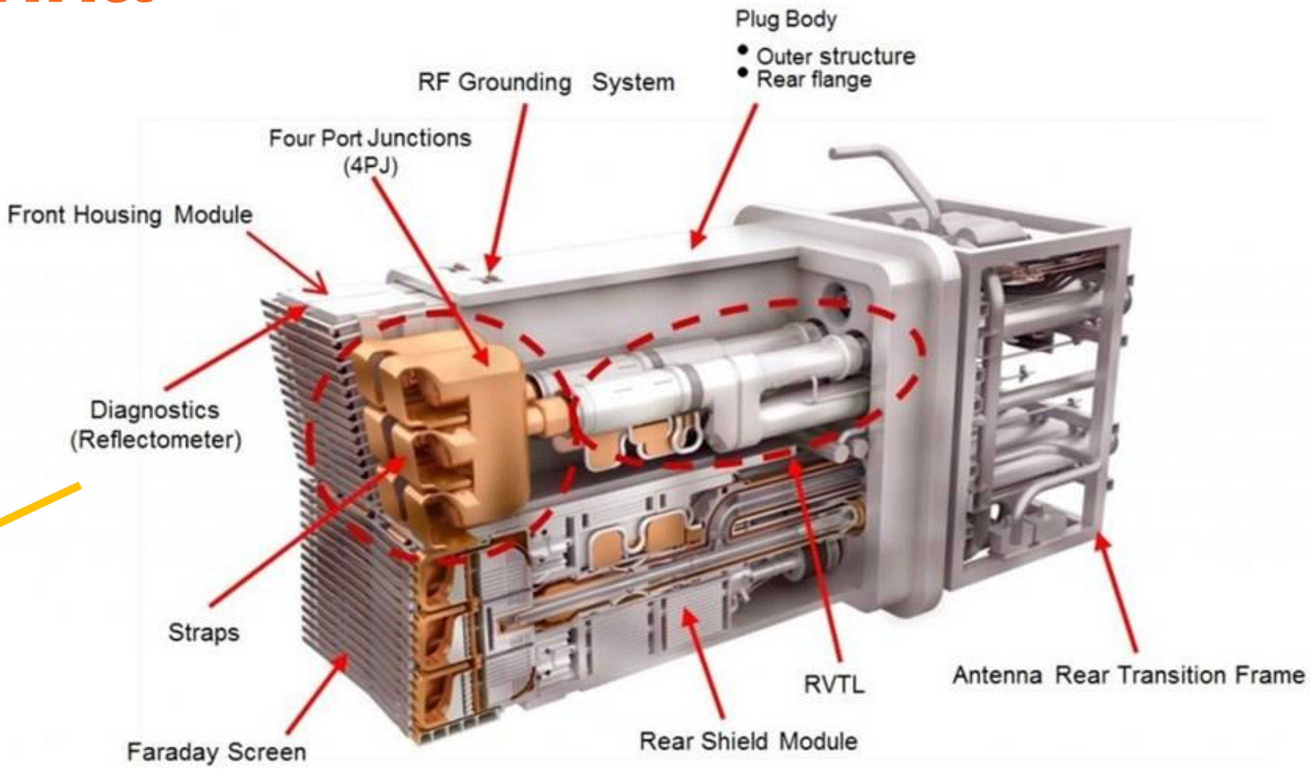



ECRH: ω ~ 28 GHz / B [T]

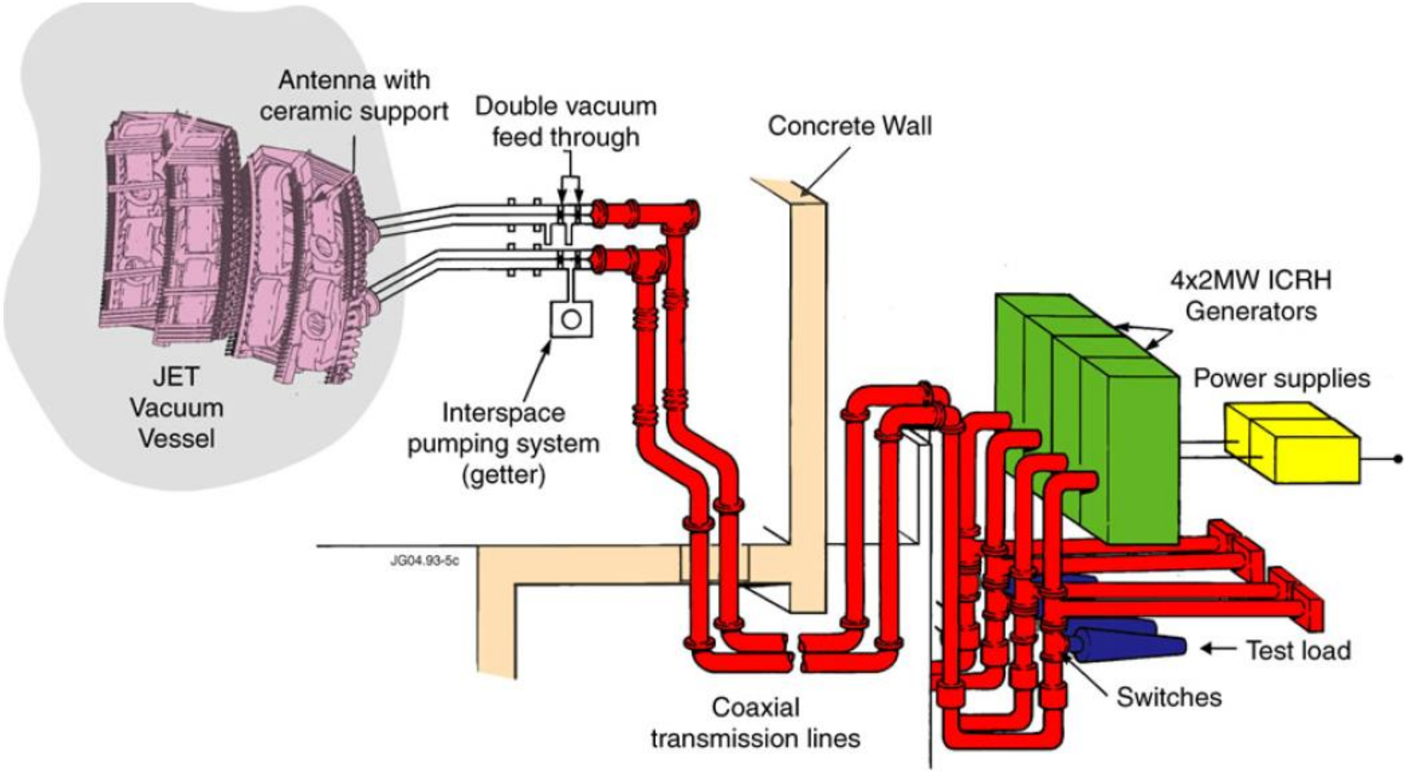
ICRH: ω ~ 15 MHz / B [T]

# ITER ICRH antenna





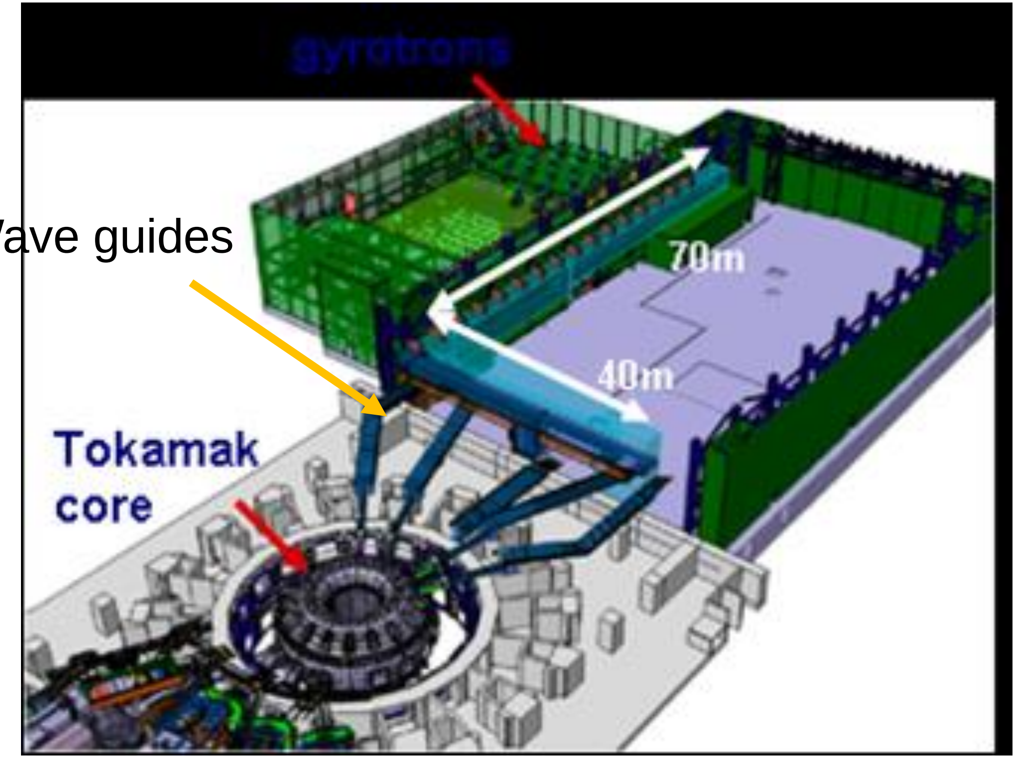
# JET ICRH system: 4 x 2 MW



# ITER ECRH system

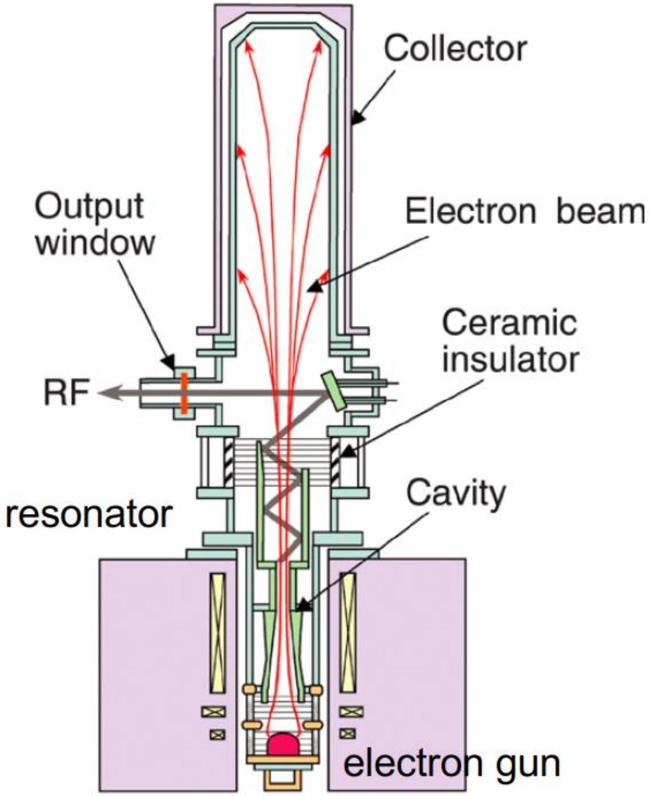
Key words:

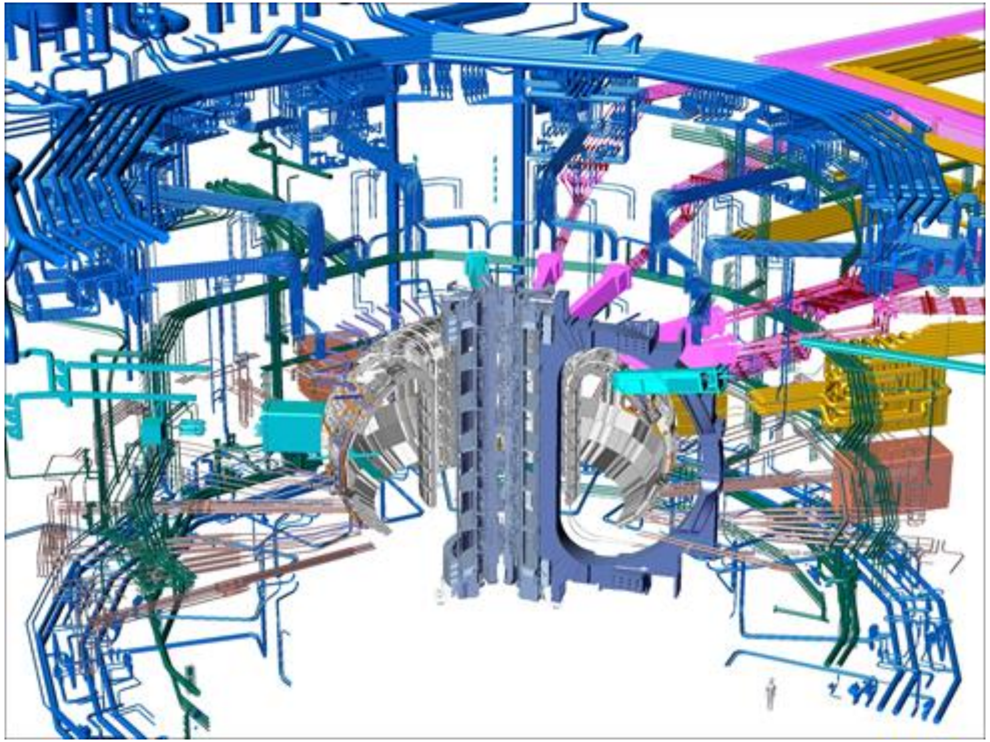
- Gyrotron
  - RF source
- Wave guide
  - Transfers the power to the plasma



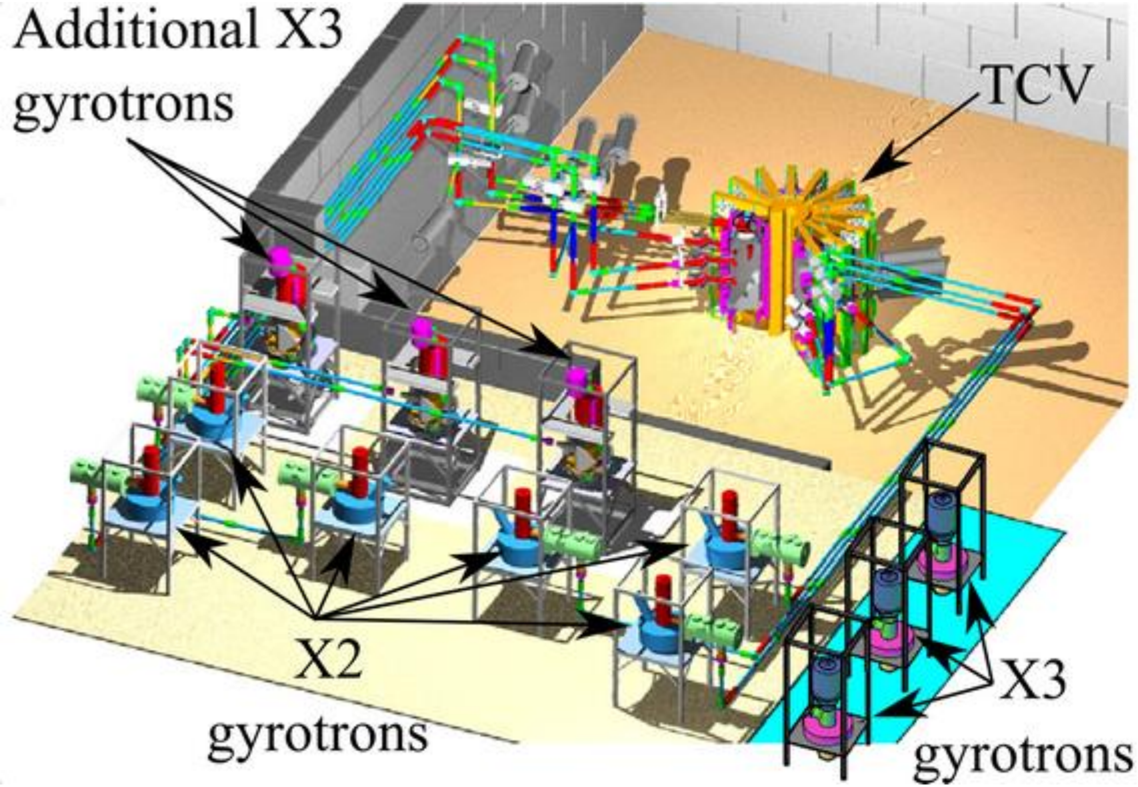

https://www.hs.fi/tiede/art-2000008759019.html

# Gyrotron and pink wave guides



# ECRH system @ EPFL, Switzerland

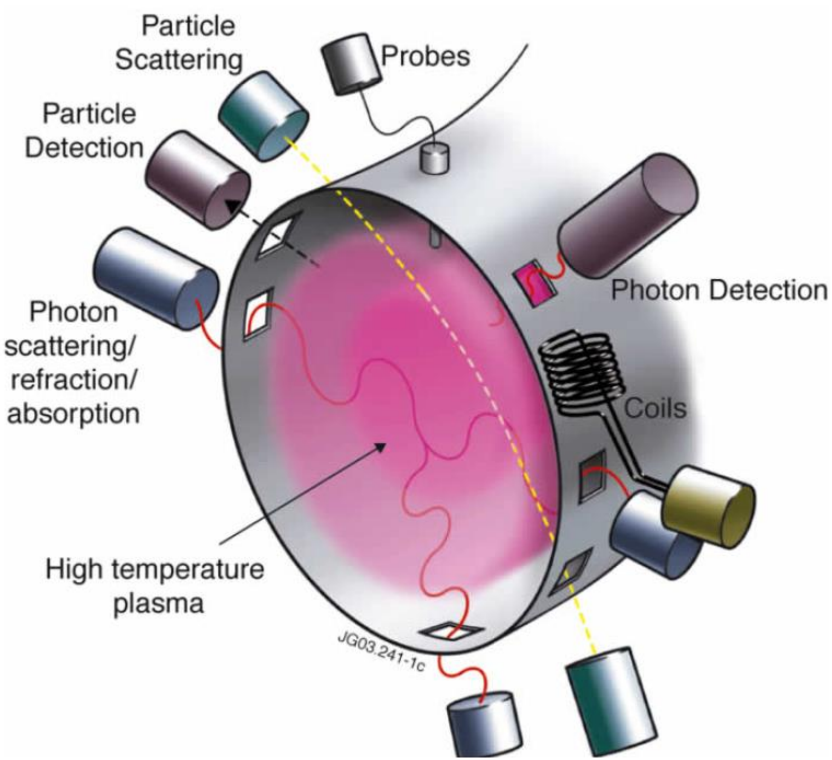


# Summary of the heating methods

| 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: $i^+$

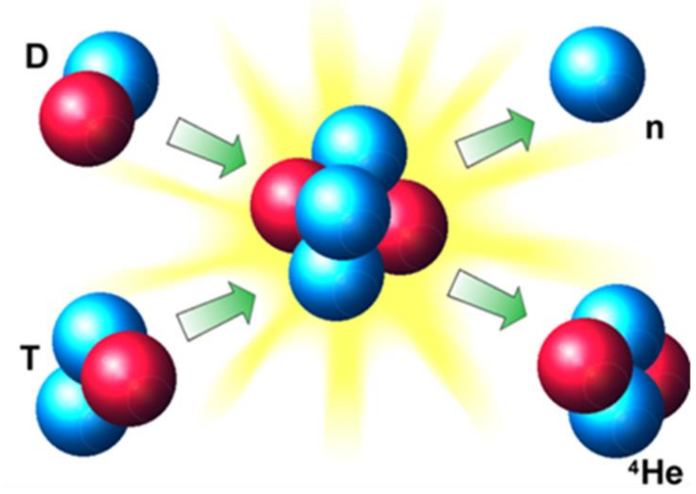
- NPA = neutral particle analyzer
  - Passive: signal along the entire line of sight ☹
- CXRS: Charge exchange resonance spectroscopy
  - Broadening of the impurity spectral lines gives the temperature!
  - Passive: signal along the entire line of sight ☹
- Active CXRS:
  - Diagnostic NBI ➔ location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



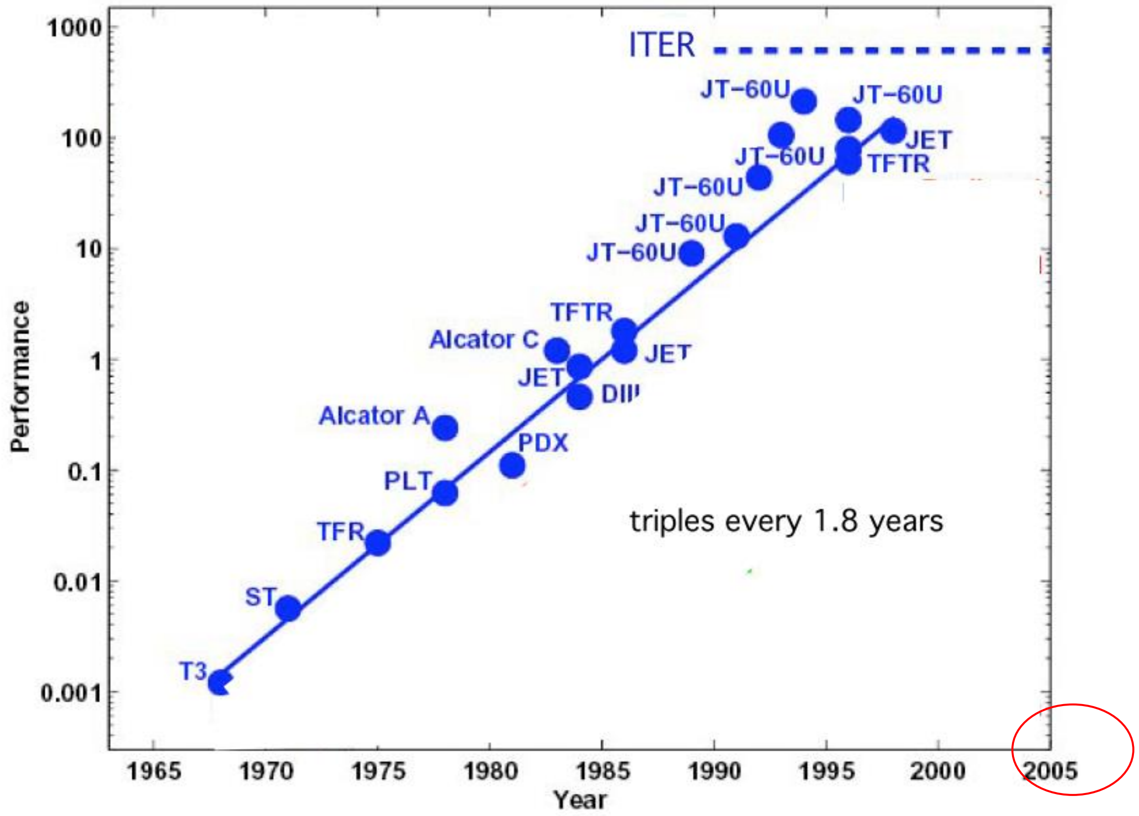

D + T
→ $^4$He + n + 100 000 kWh/g

# Summary of the diagnostic methods

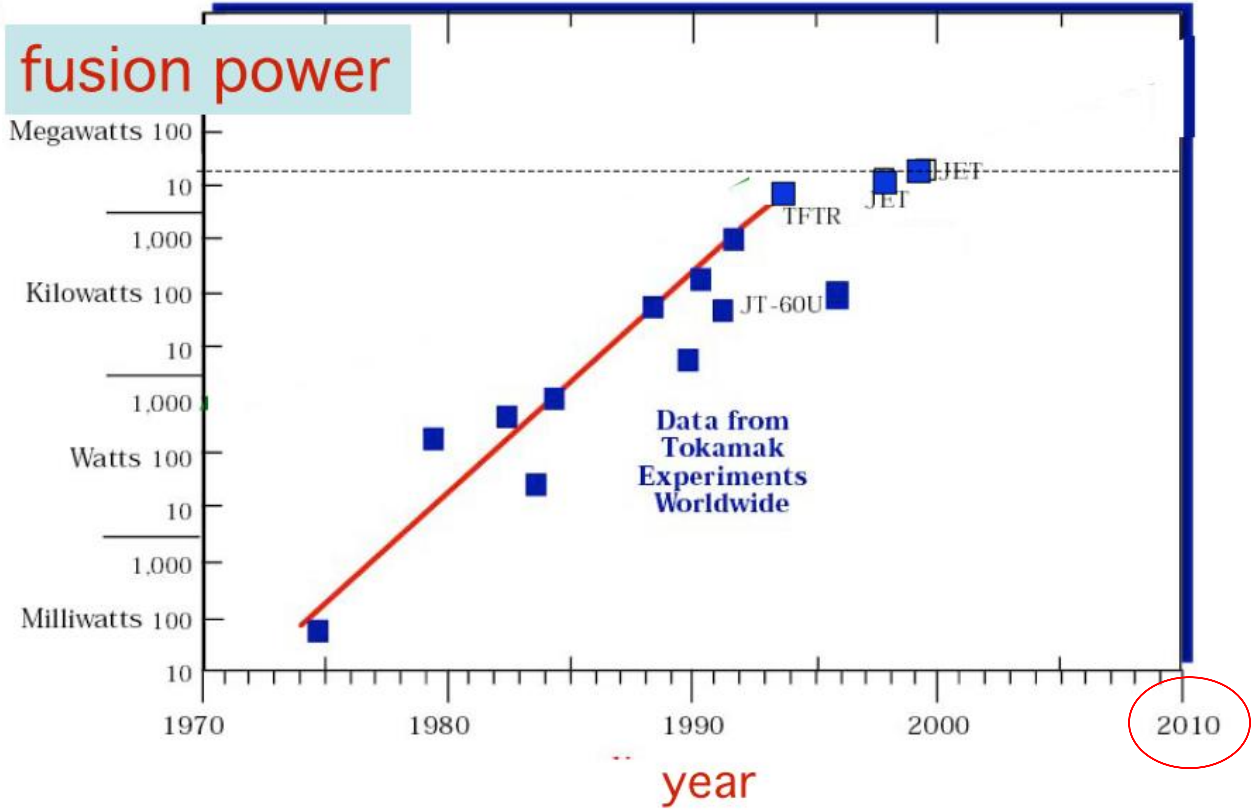
| Category | Parameter | Method |
|---|---|---|
| Magnetics | Plasma current<br>Loop voltage (Ohmic power, $T_e$)<br>Diamagnetic energy<br>Plasma position/equilibrium | Rogowski coil<br>Voltage loops<br>Diamagnetic loop<br>Poloidal field coils |
| Passive radiation | Electron temperature and densities, 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 …



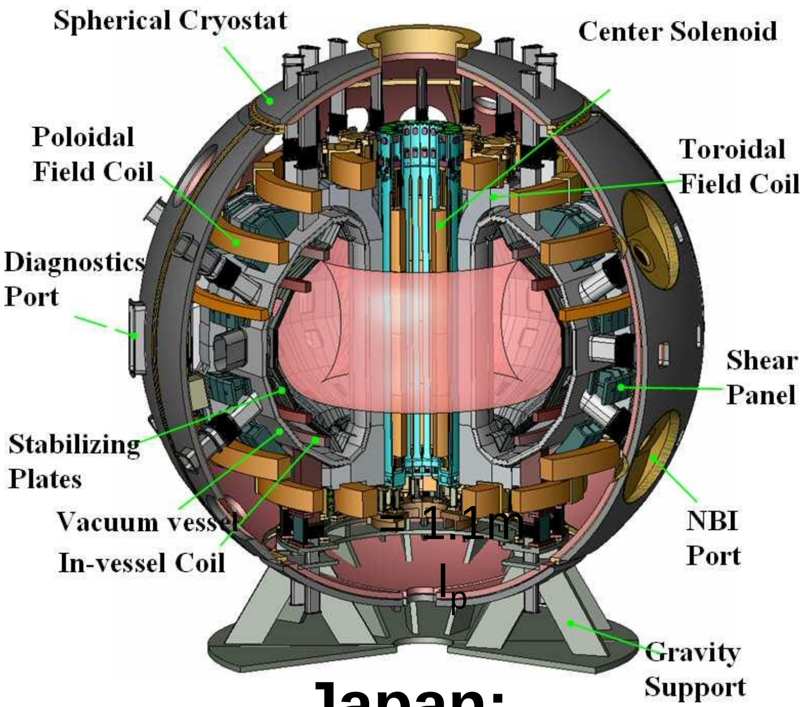
# Breakthroughs in fusion research

- 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 = ”the way”(under construction 2010 -- 2020’s)

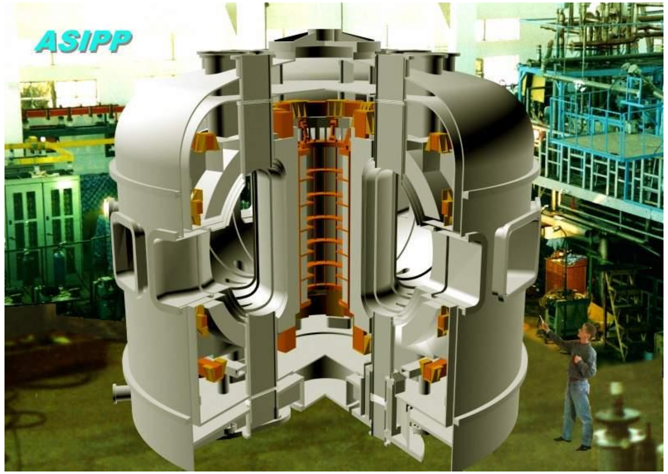
# But JET is already very old and fragile … don’t we have something new and better?

# 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

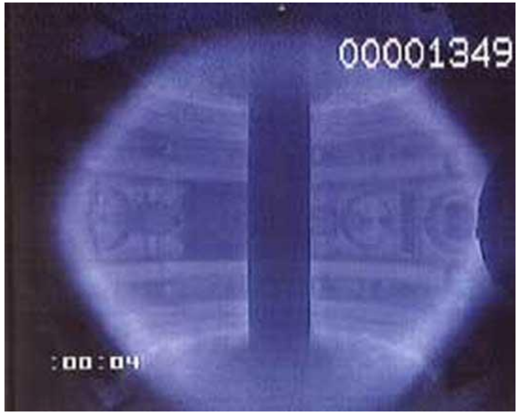



**China:**
*EAST*
R = 1.7m,
a = 0.4m
$I_p$ = 0.5MA
$B_T$ = 3.5T

# 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

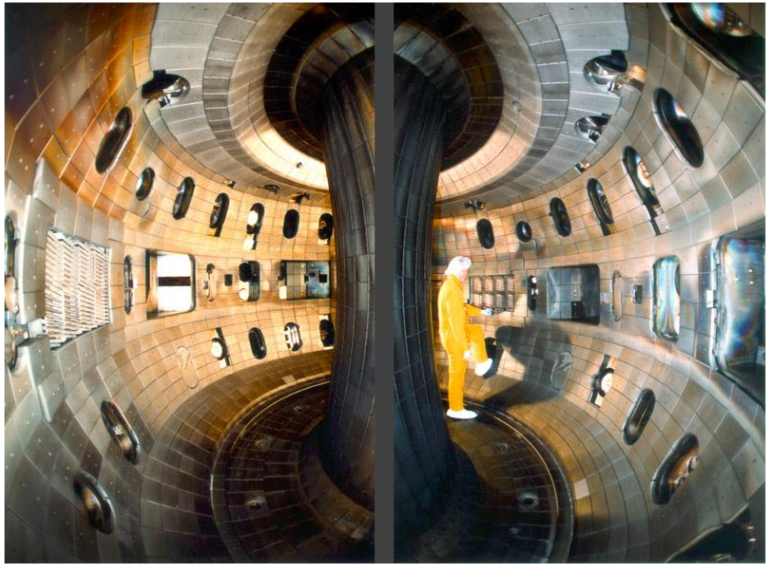
**JET**
*Culham, England*
LARGE, high performance
R = 3m, a = 1.3m
$I_p$ = 4.8MA, $B_T$ = 3.5T




**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

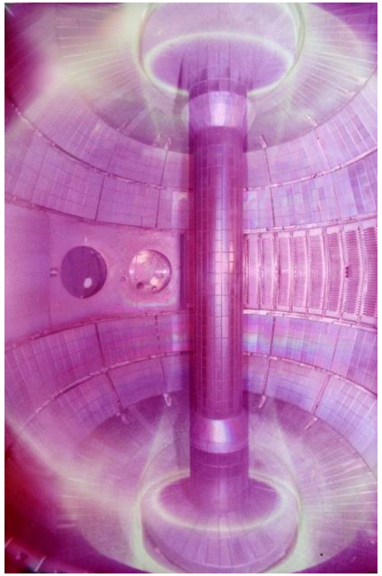


**DIII-D**

*General Atomics*

R = 1.7m, a = 0.7m

$I_p$ = 2MA, $B_T$ = 2.2T



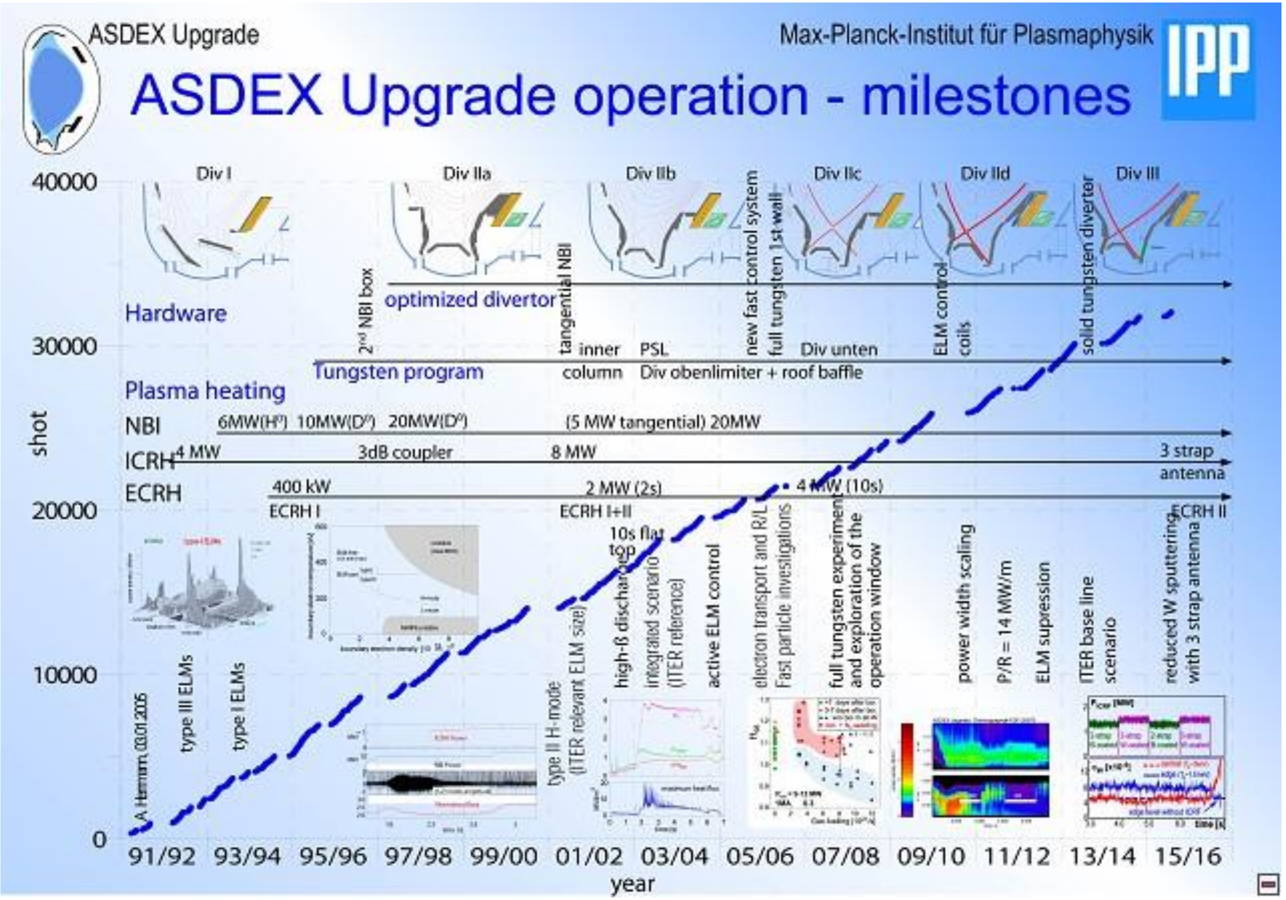
**NSTX-U**

*Princeton*

R = 0.85m, a = 0.68m

$I_p$ = 1.4MA, $B_T$ = 0.3T

… but being fixed for N years… ☹

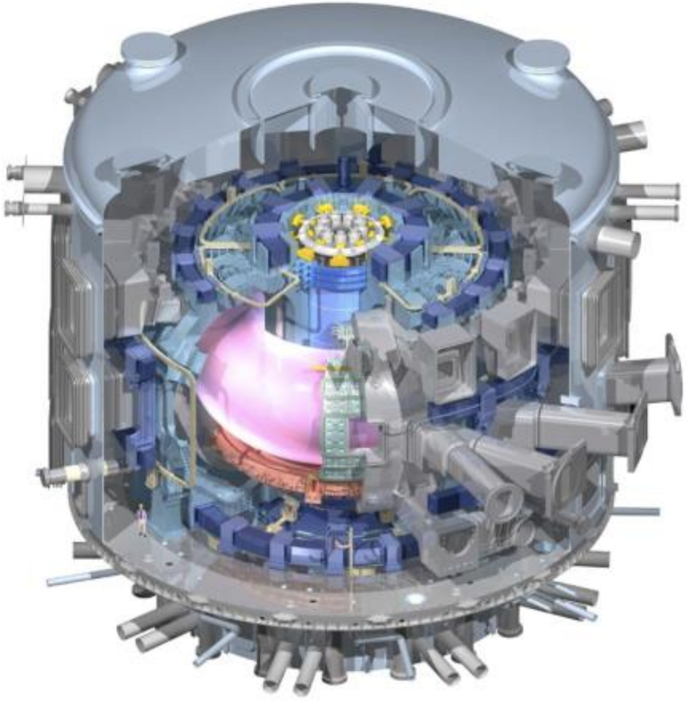



## http://www.ipp.mpg.de/1728289/panorama : AUG

# And our goal is … *energy !*

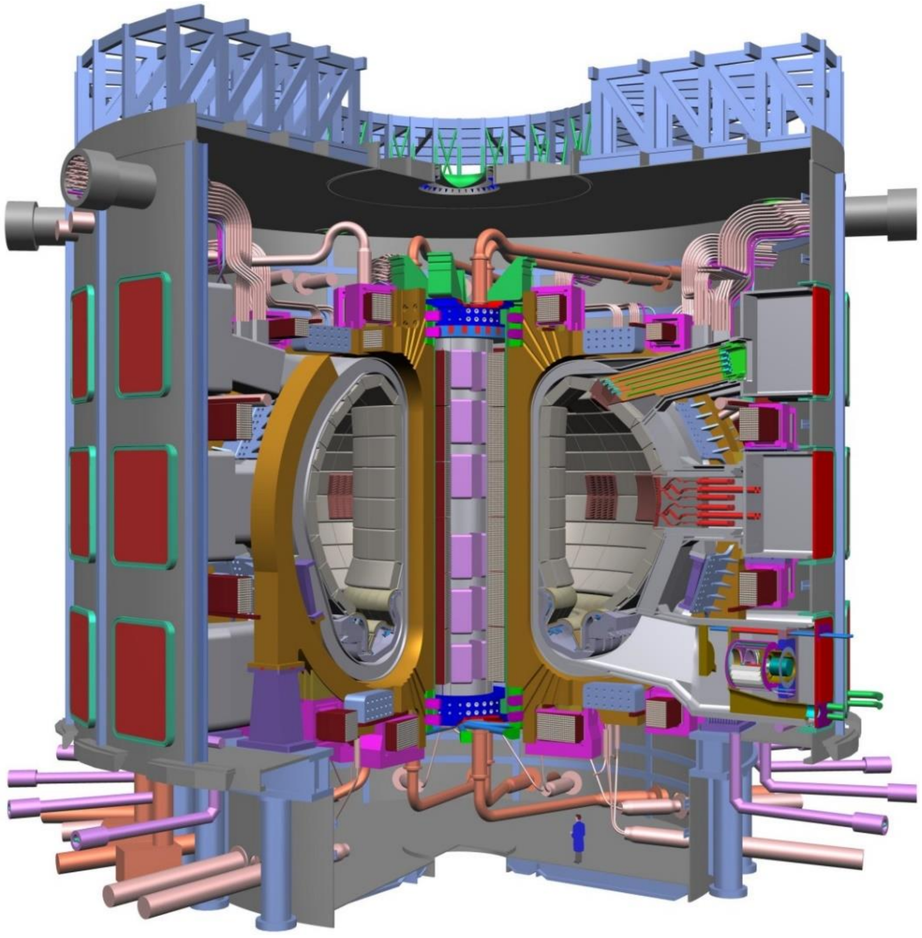
# ITER = the first fusion *reactor*

| | 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

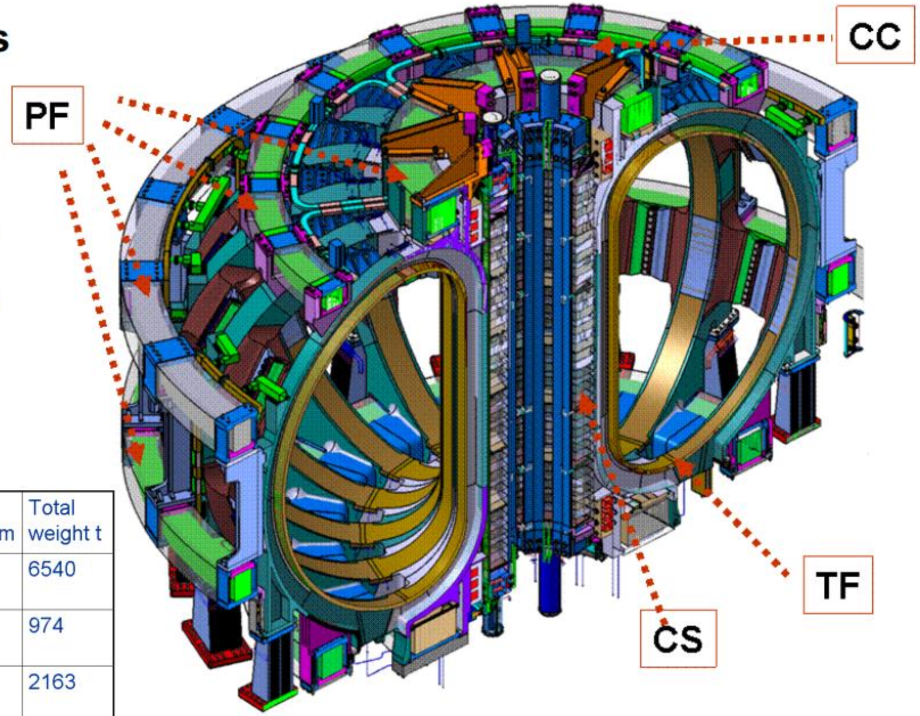
- Plasma conditions similar to expected power plant
- Technical specs:
  - Total fusion power: 500 MW
  - Q = Fusion power/aux. heating power ≥ 10
  - Plasma major radius: 6.2 m
  - Plasma minor radius: 2.0 m
  - Plasma current: 15 MA
  - Toroidal field at 6.2 m: 5.3 T
  - Plasma volume: 837 $m^2$
 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



Yleismies Jantunen röörejä tsiikaamassa

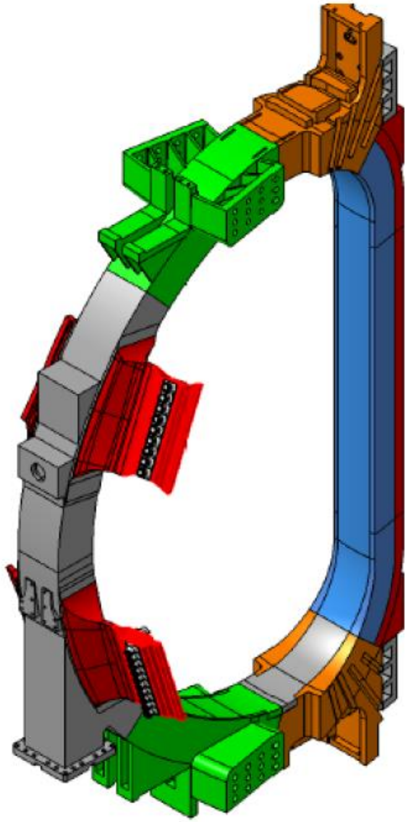
# ITER is not a small device …

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



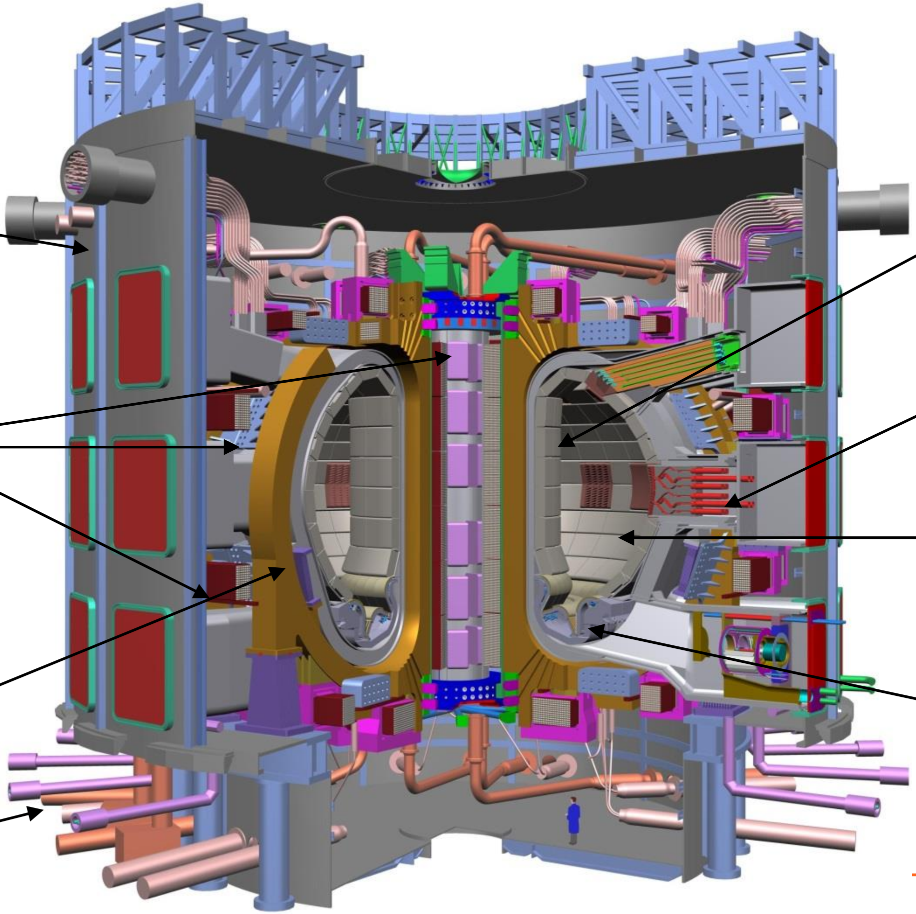

| System | Energy GJ | Peak Field | Total MAT | Cond length km | Total weight t |
|---|---|---|---|---|---|
| Toroidal Field TF | 41 | 11.8 | 164 | 82.2 | 6540 |
| Central Solenoid | 6.4 | 13.0 | 147 | 35.6 | 974 |
| Poloidal Field PF | 4 | 6.0 | 58.2 | 61.4 | 2163 |
| Correction Coils CC | - | 4.2 |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

# A TF coil vs Boeing 747-300 …



TF coil: 360 t

# ITER main components



# ITER construction site 2011

# ITER Construction site Dec 2012

# ITER Construction site Feb 2015

Iter.org

# ITER Construction site Feb 2016

Iter.org

# April 2016

# December 2017

# They have moved indoors already….

# Familiar faces? (November 2022)

# 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

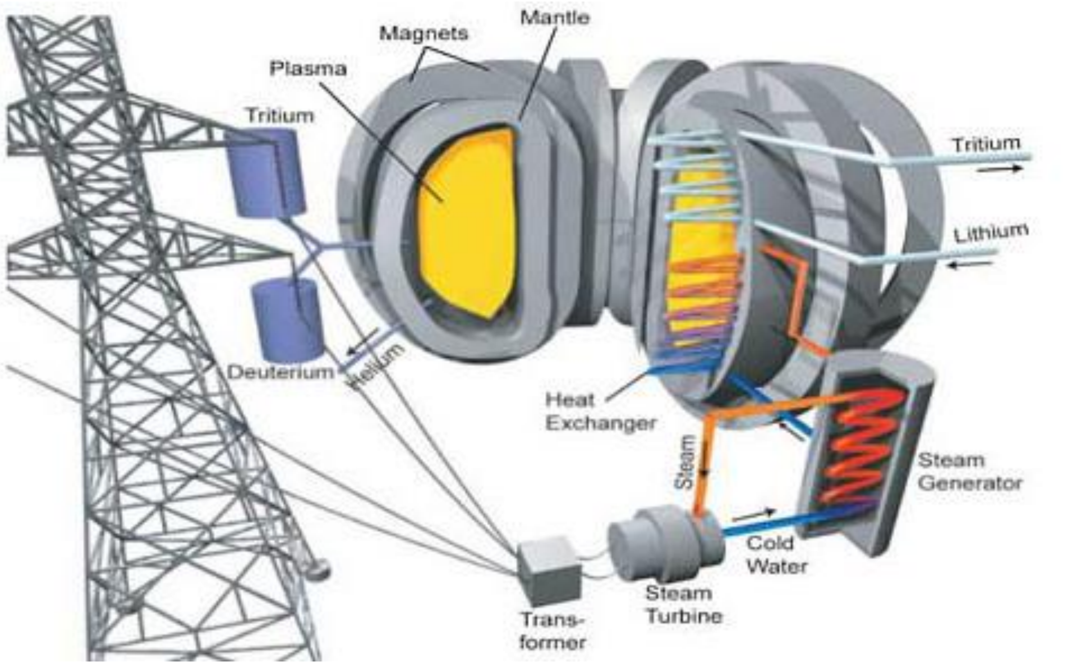
- High plasma current: up to 5.5 MA
- High energy *negative* neutral beams: 10 MW of 500 keV N-NB
- super-conducting coils ➔ long pulses (100s)
- Two sizes of TBM mock-ups (?)

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

# And our goal is … *electricity* !

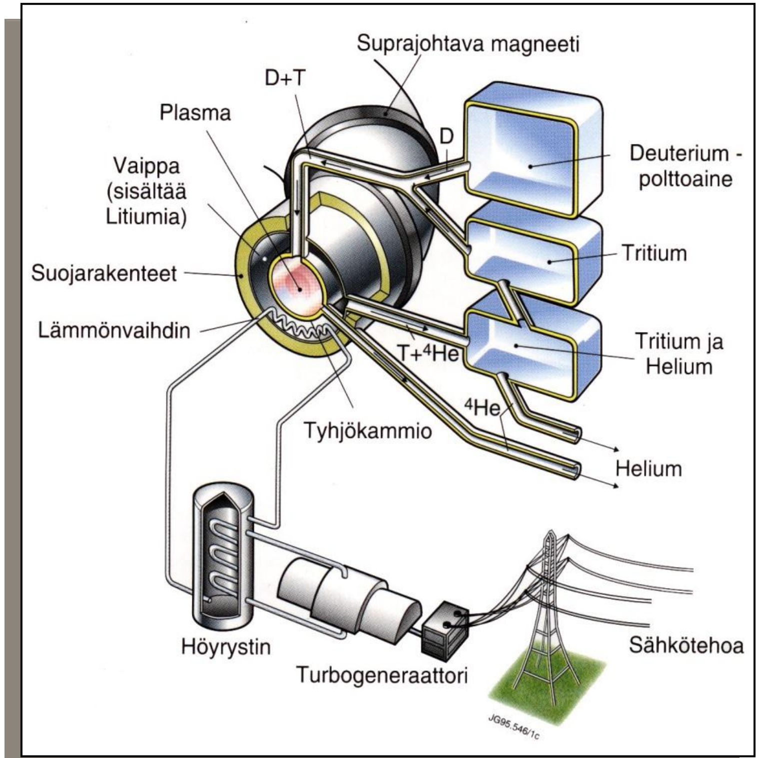
Aalto University
School of Science

# 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



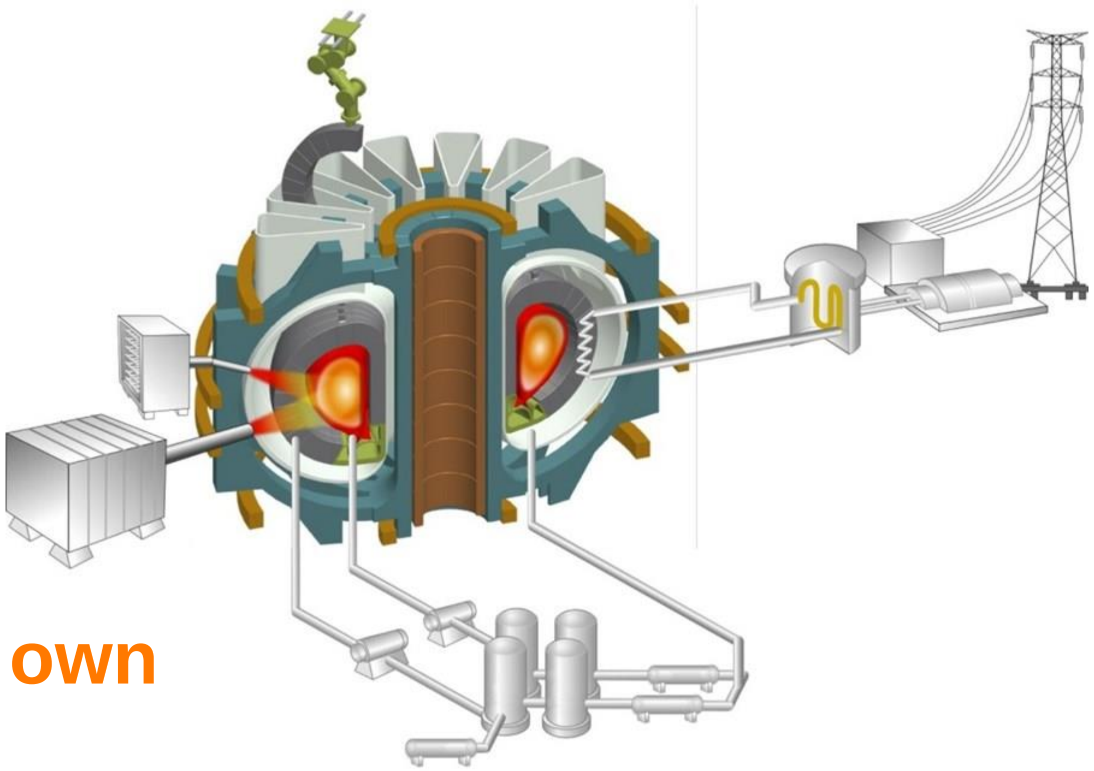
# Various designs: DEMO-CREST based on ITER @$P_{fus}$ = 10x$P_{aux}$; ARIES-AT, EU DEMO

- 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* !

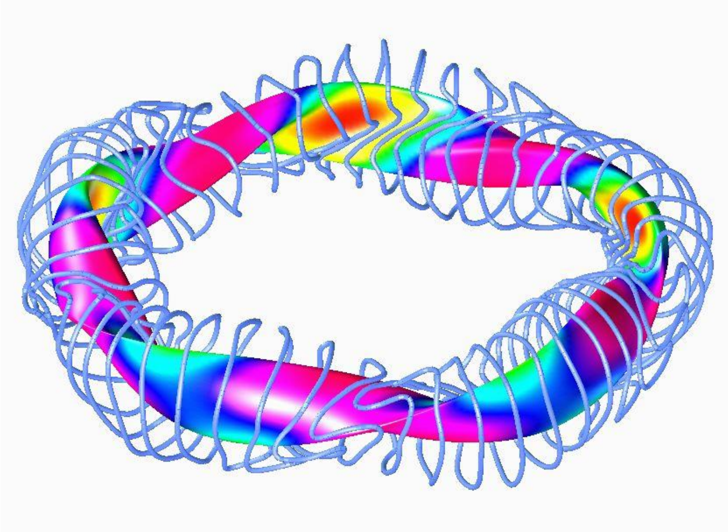
# A stellarator -- Fusion with a twist …

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** !

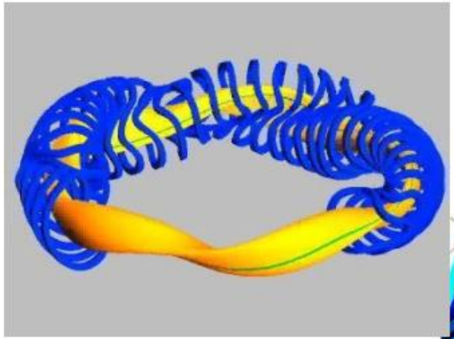


No plasma current ➔

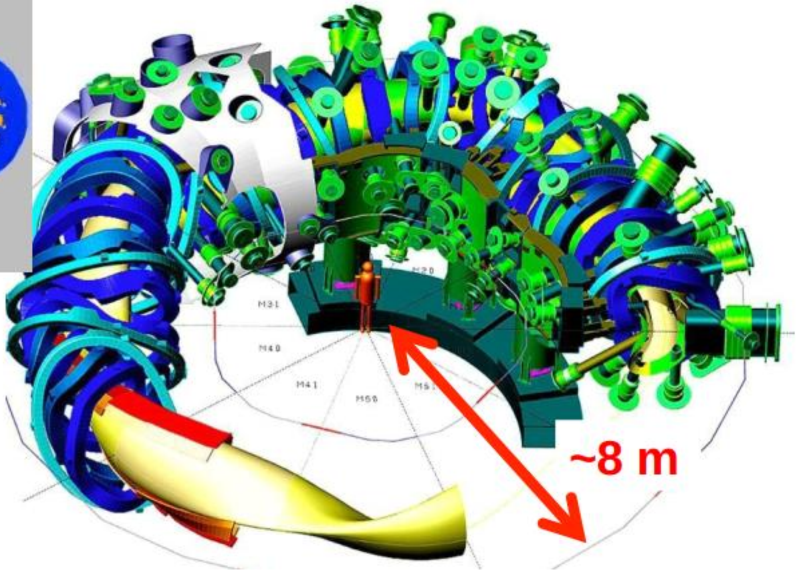
- Continuous operation!
- MHD quiescent plasma !

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

- HELIAS ("pure stellarator") ⇒ drift-optimized

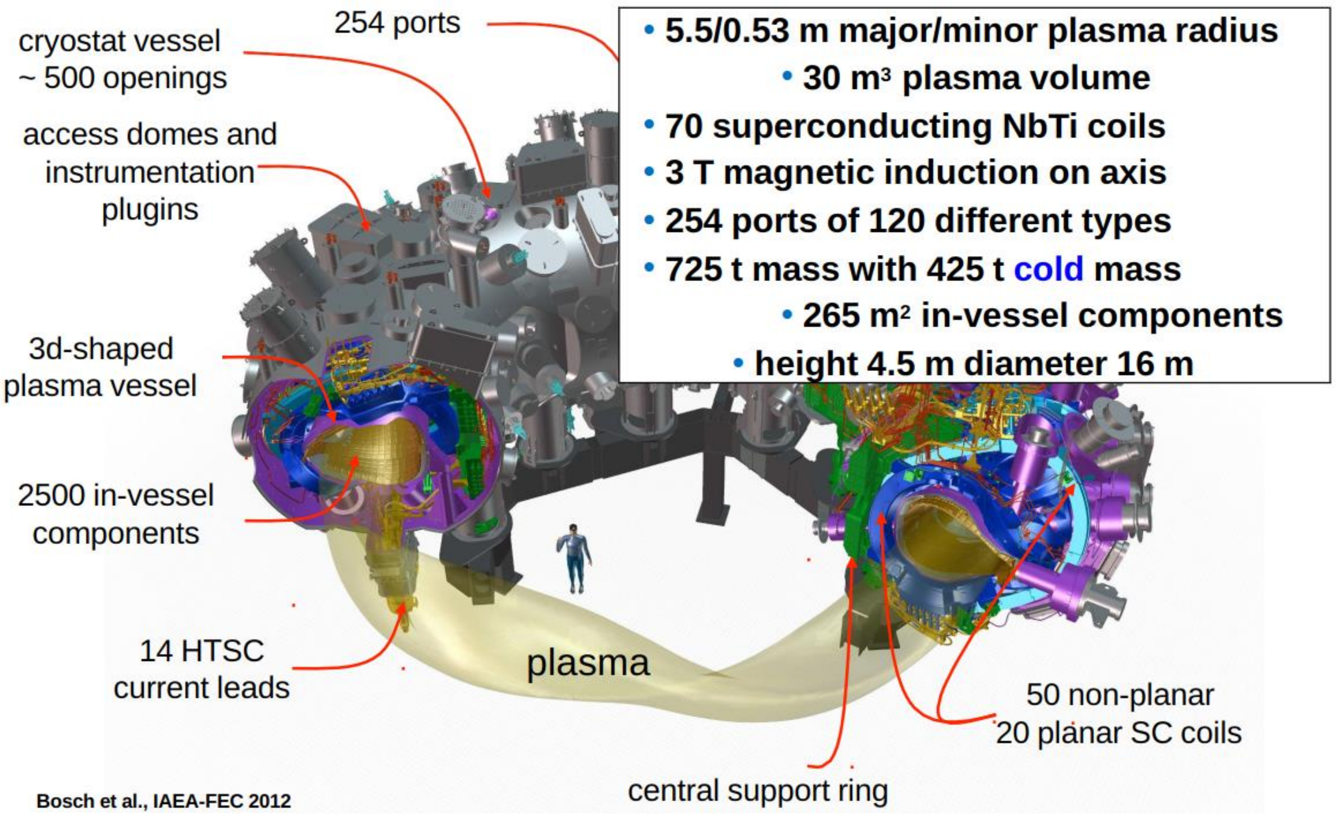


- R=5.5 m, a=0.52 m, $V_{plasma}$~30 $m^{-3}$
  (vs. JET: 3/1/100 and ITER 6/2/840)



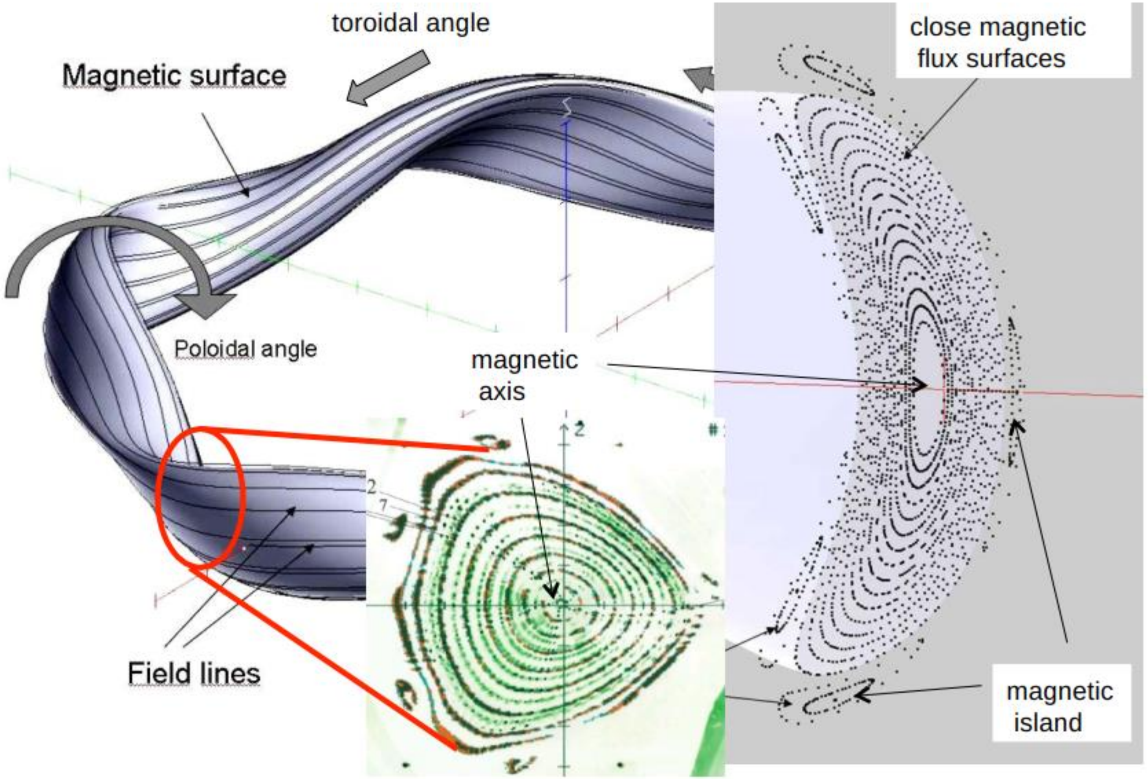

- Fully cooled in-vessel components and island divertor

# … but an engineer's nightmare?



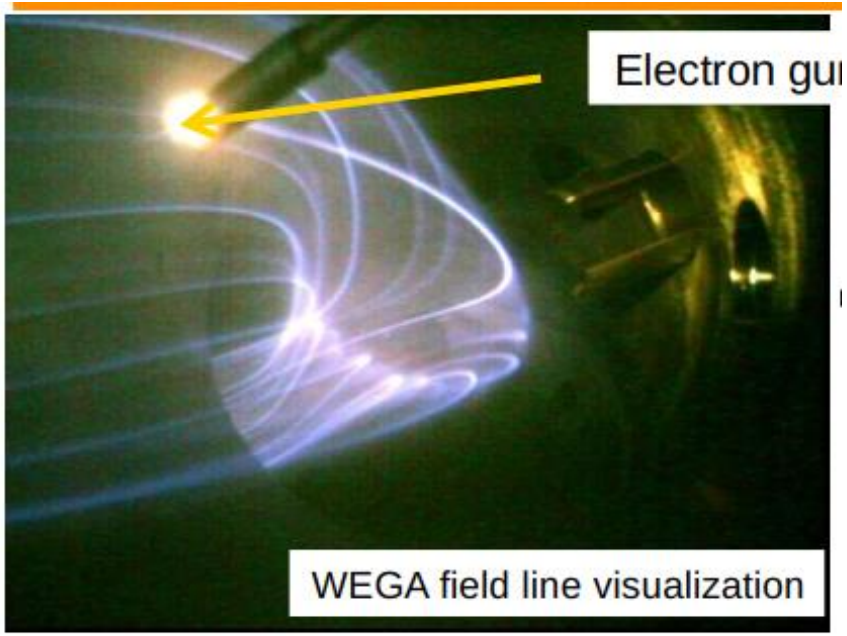

Bosch et al., IAEA-FEC 2012

# Kiss symmetry goodbye …

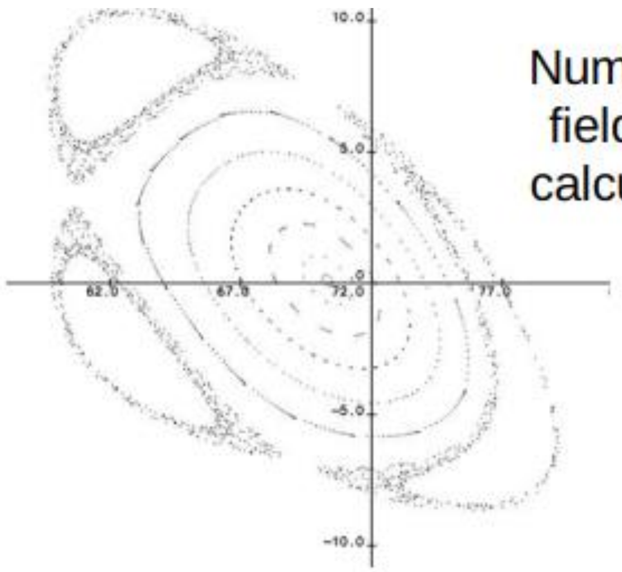


# Vessel walls ’lick’ the plasma

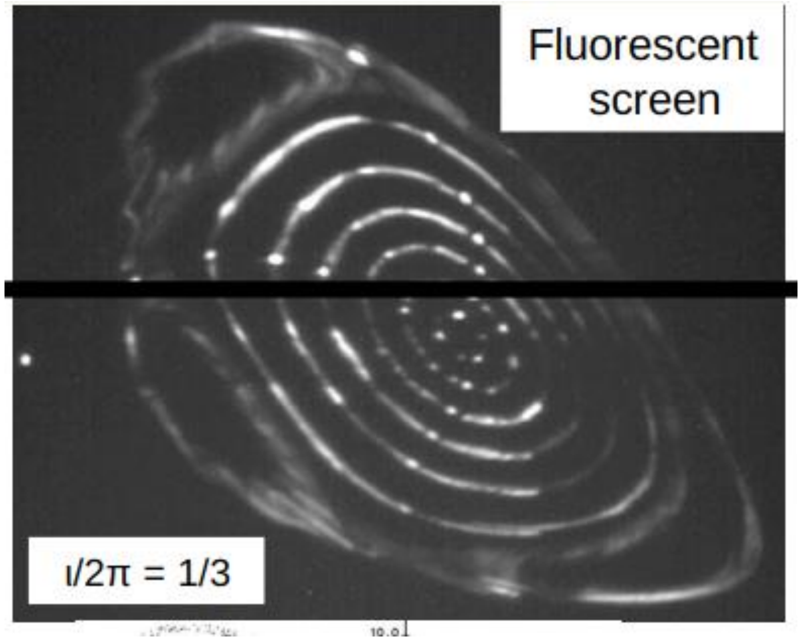
# Stellarator too complicated for pen-n-paper → optimized with super-computers …



# … and verified by experiments !



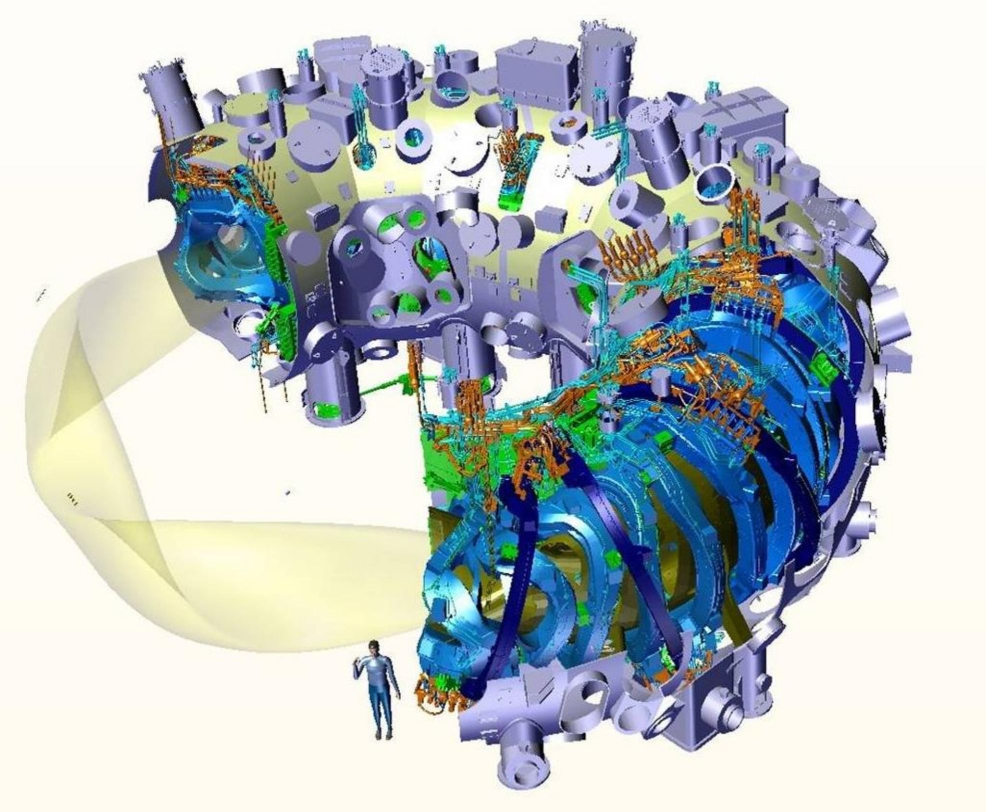

Numerical field line calculation



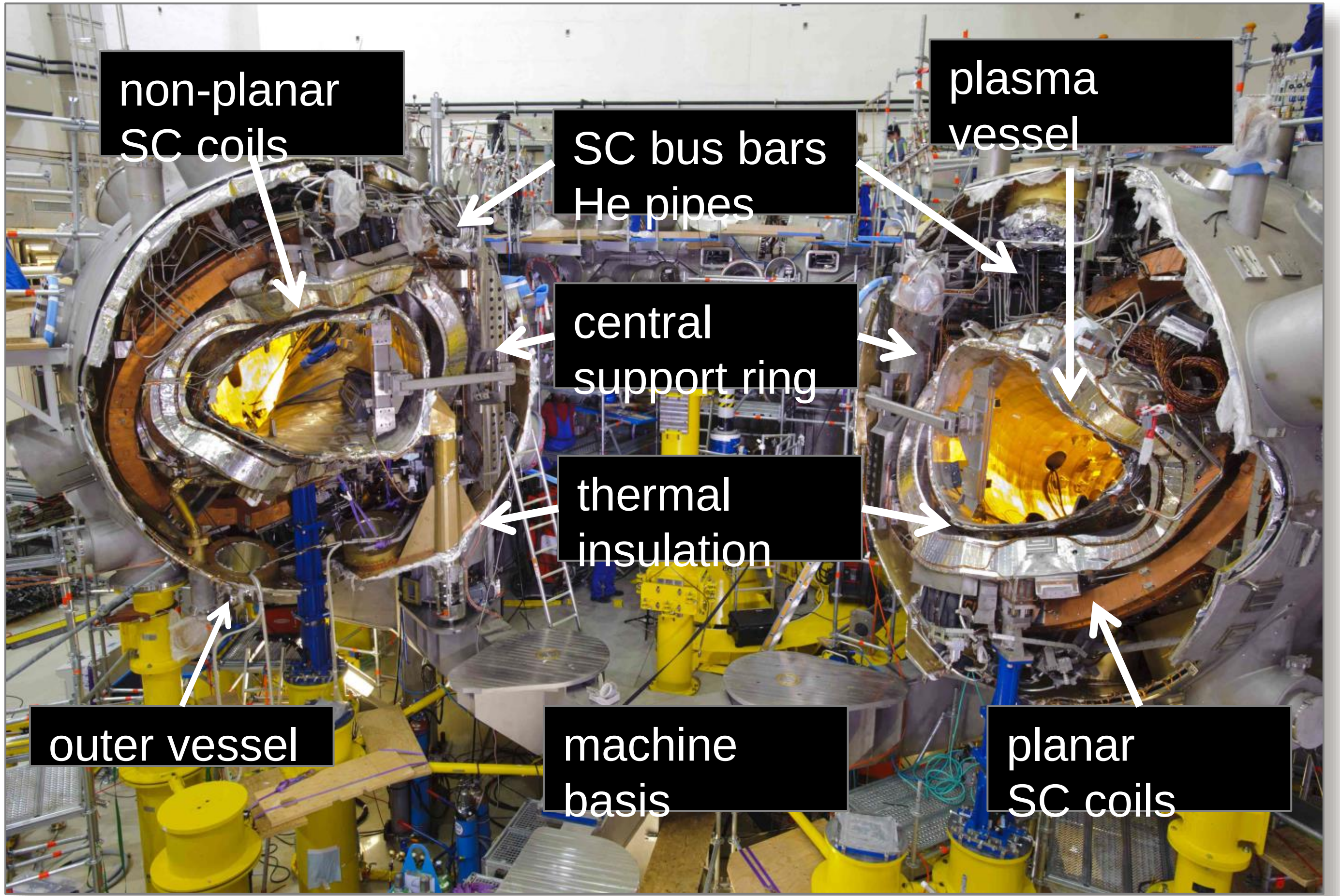

Electrons emitted parallel to calculated B in vacuum field without plasma ⇒ fluorescent projector and interaction with (Ar) background gas

# Wendelstein 7-X, technical data

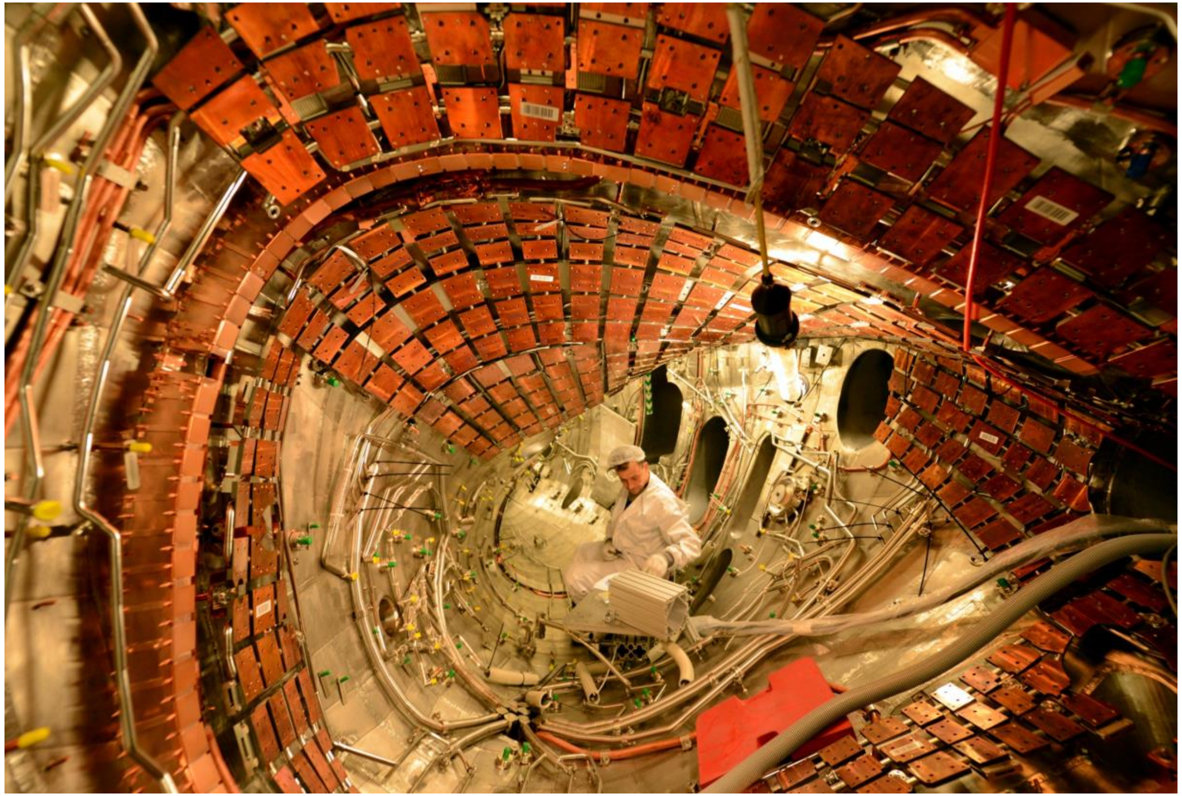
| | |
|---|---|
| major radius | 5.5 m |
| minor radius | 0.53 m |
| plasma volume | 30 $m^3$ |
| machine mass | 725 t |
| cold mass | 425 t |
| | |
| non-planar coils | 50 |
| planar coils | 20 |
| induction on axis | 2.5 - 3 T |
| stored energy | 600 MJ |
| heating power | 15 - 30 MW |
| pulse length | 30 min |



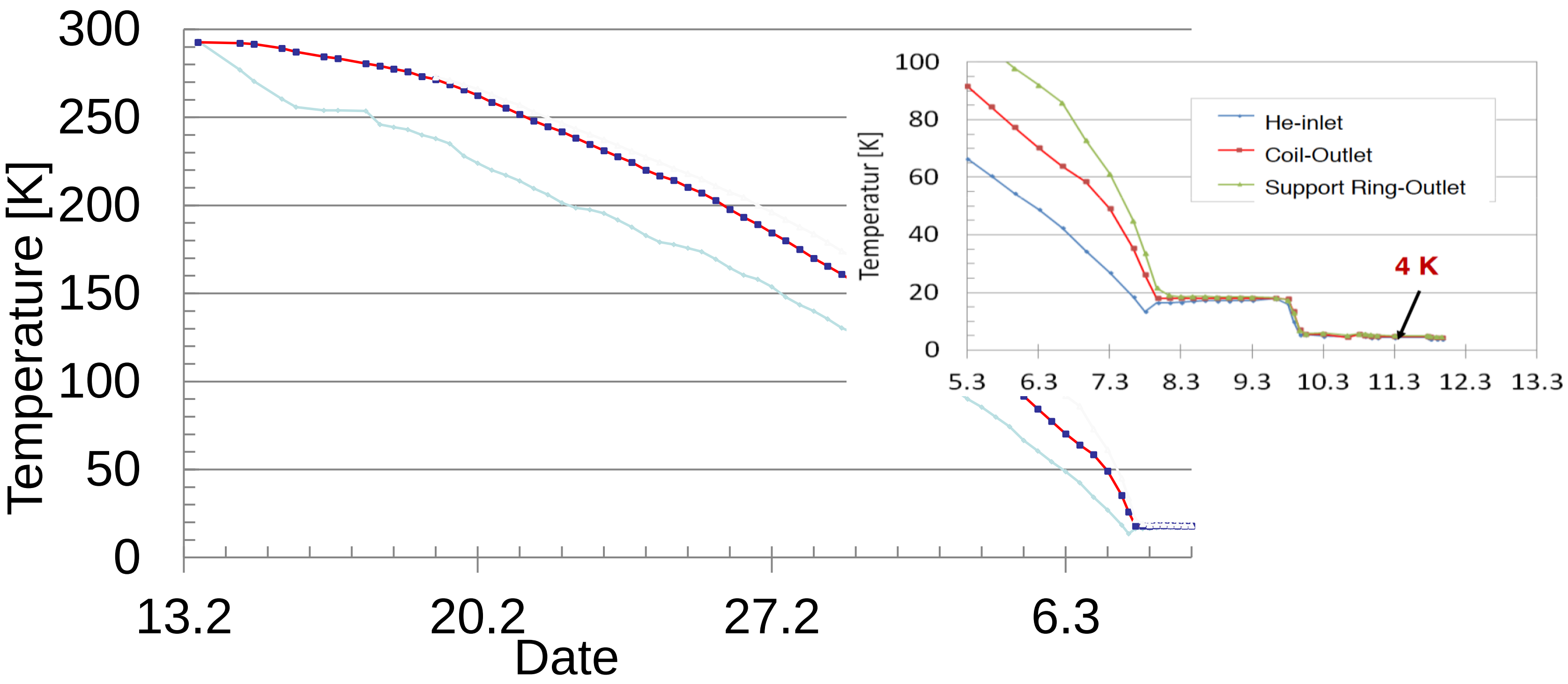
# Under construction



# Decoring the interior …



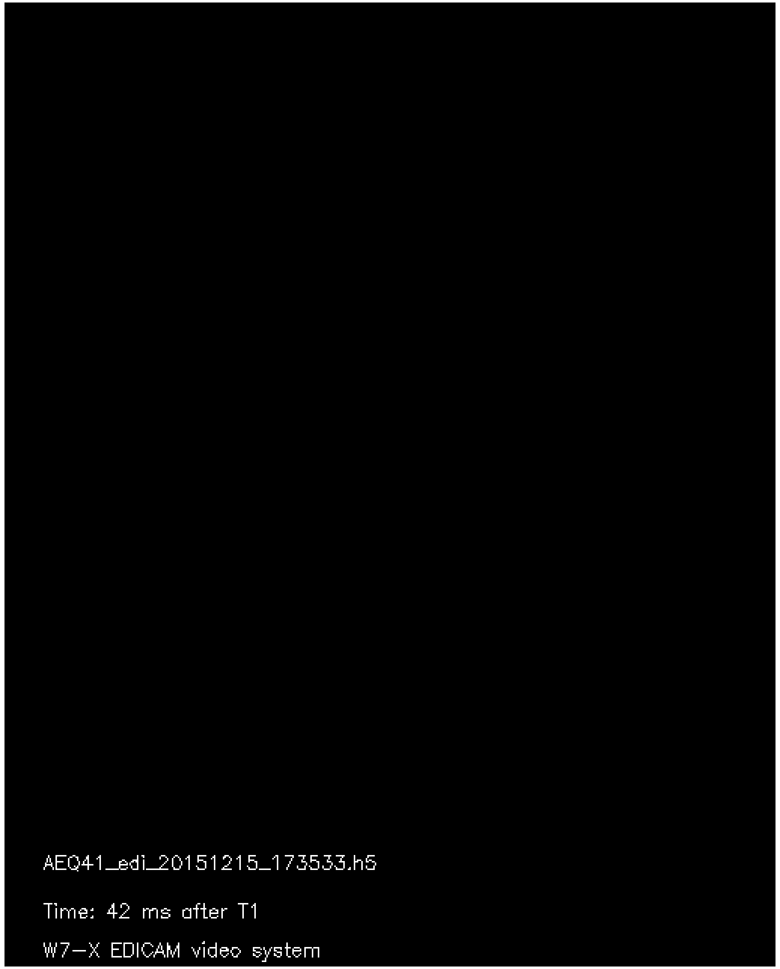
# Commisioning 2015: cooling the superconducting coils



# First plasma shots 2016

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

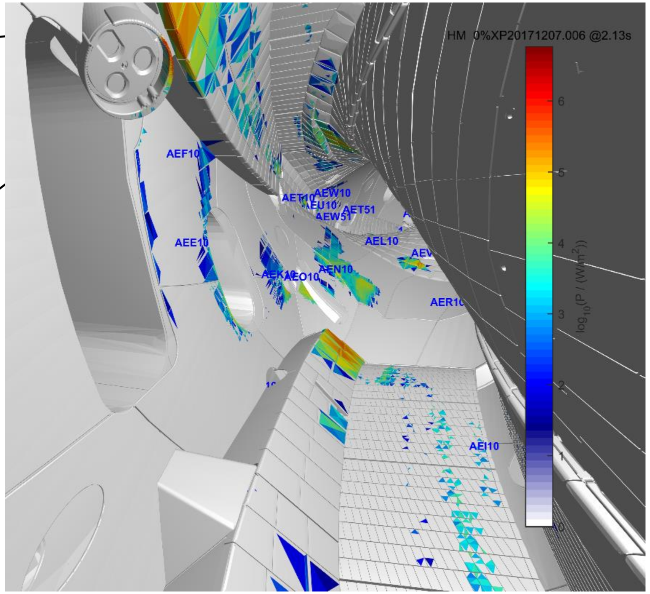
- Ultimate goal, when all bells and whistles installed:
- 2022 or so:
  - ~10 keV (ions),
  - Plasma duration ~30 minutes



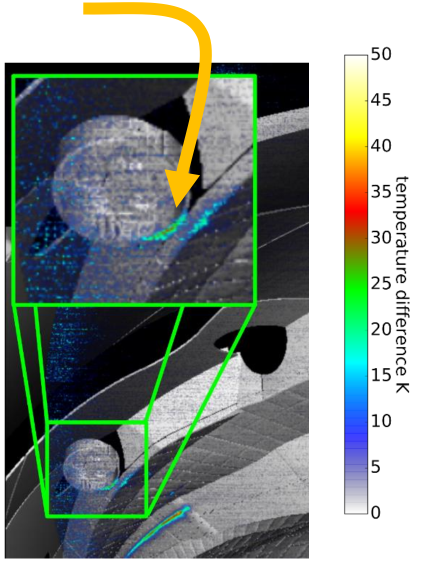
# Wall design improved thanks to ASCOT simulations !

Fragile (sapphire) vacuum windows

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

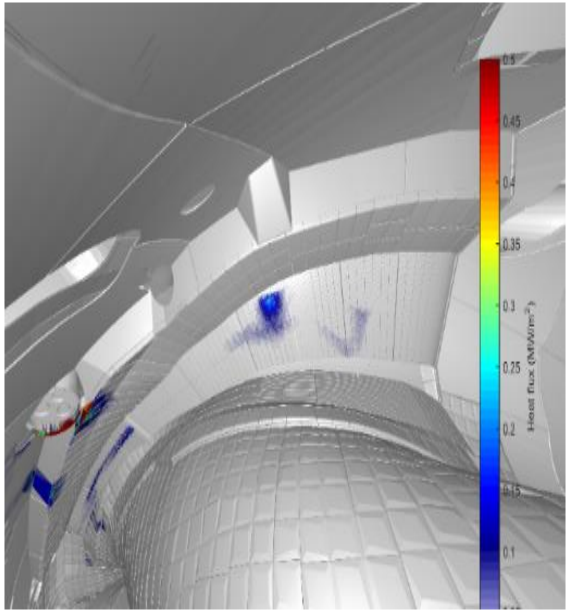



Wendelstein 7-X á l'ASCOT

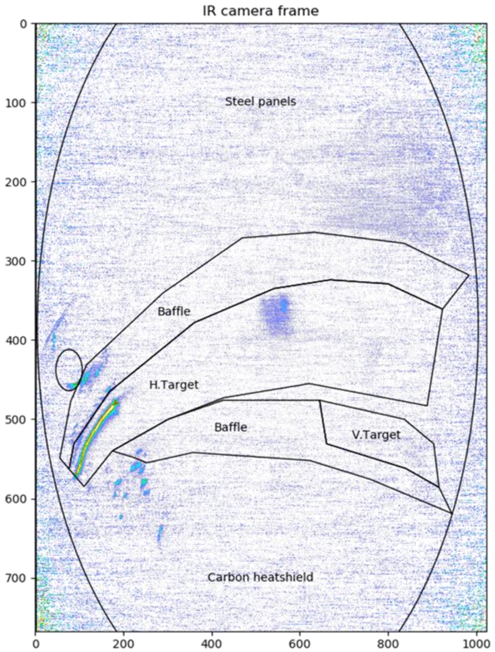



power loads in excess
of 1.5MW/$m^2$ measured

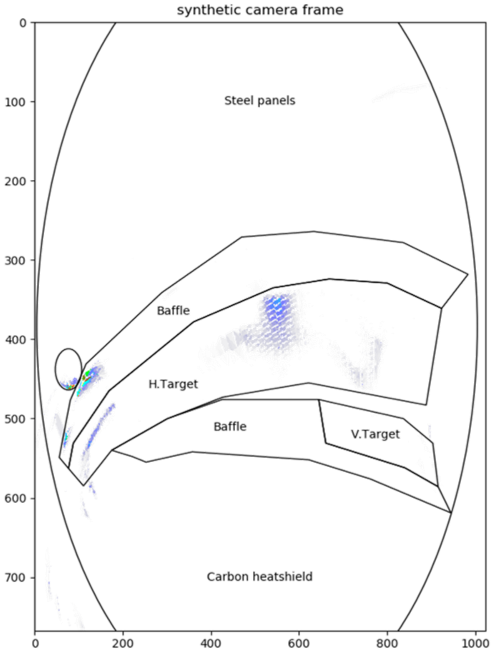
# Experimental measurement reproduced by ASCOT !



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 …***

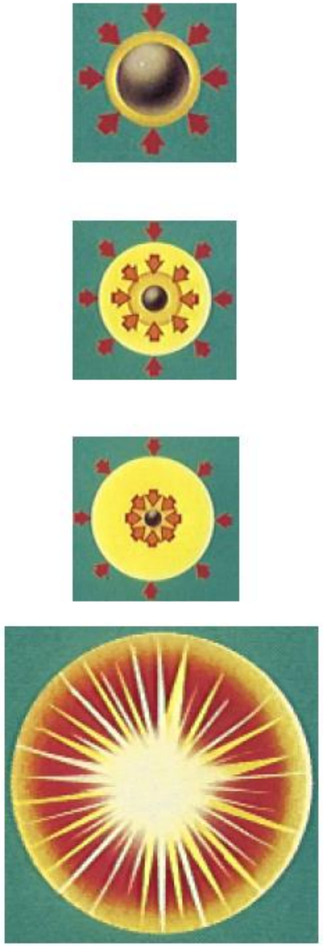
# Rivals for traditional approaches …

# 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

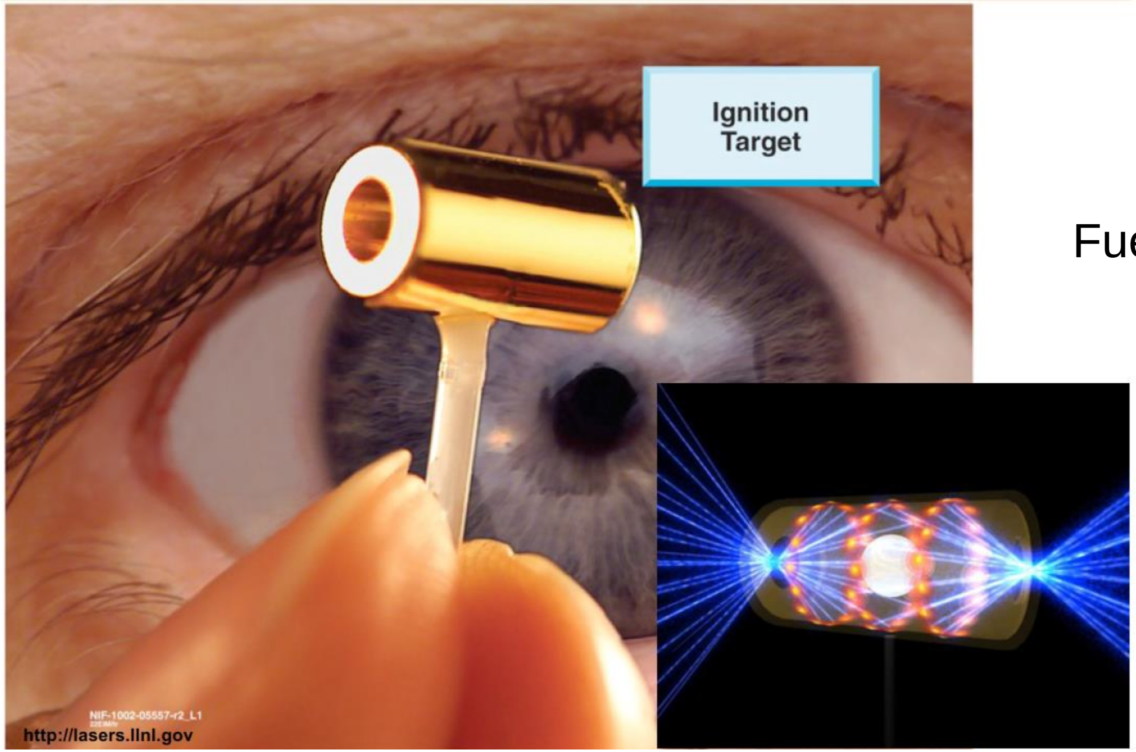
- Heat the surface of the capsule with radiation
- The fuel is compressed with surface ablation and rocket principle
- An enormous pressure is built in the core and the fuel ignites
- Followed by the burn phase



# Lawson criterion reaches new heights

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

# Laser fusion -- tiny hydrogen bomb…

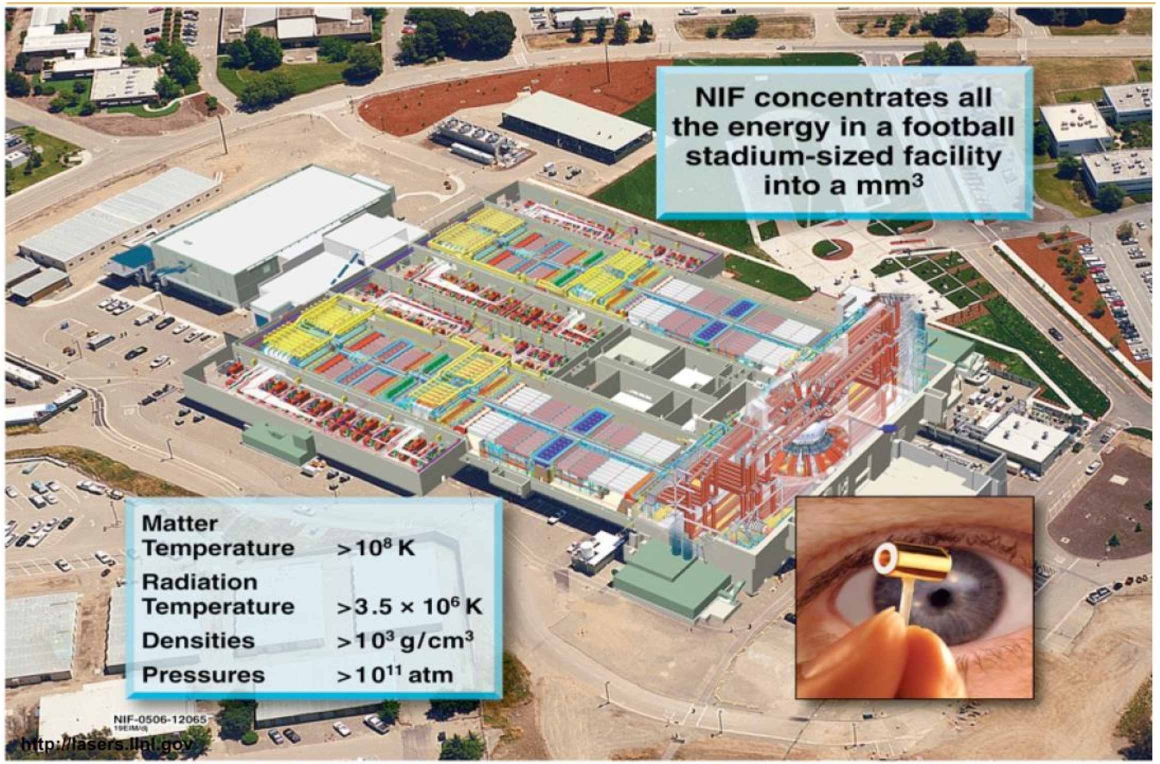



Fuel capsule’s size < cm

# Target chamber is a little larger to compensate

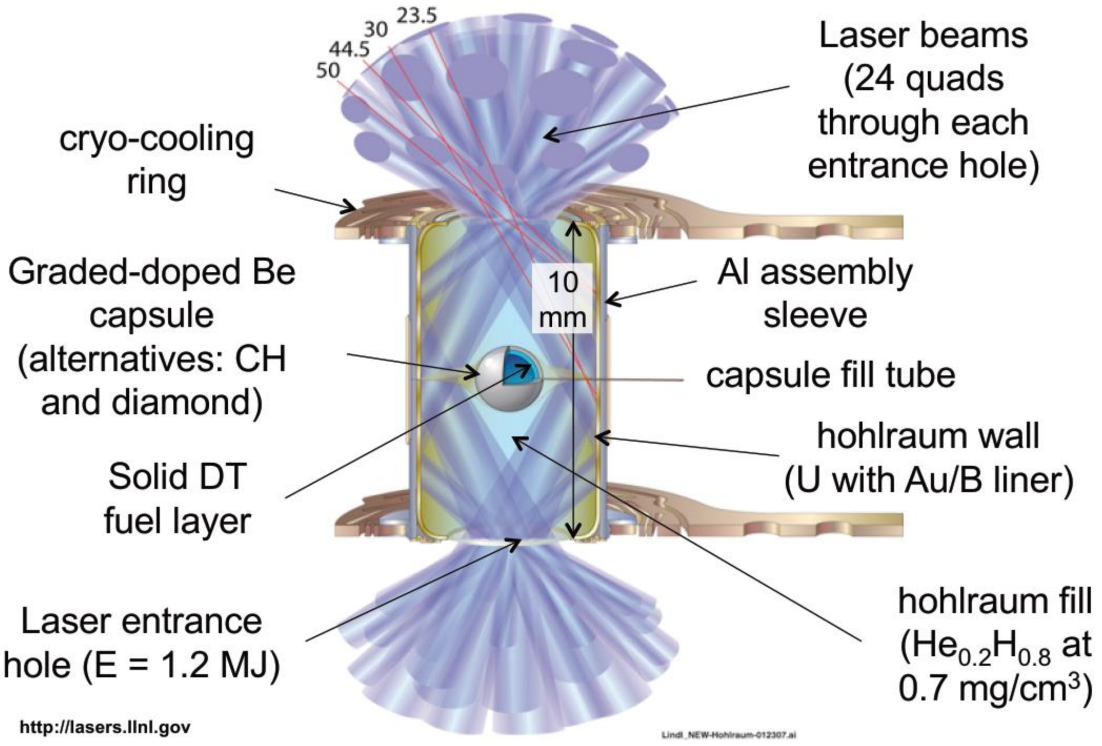

The NIF chamber has the radius of 10 m and weighs 130 tons

# The lasers take even more space …




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

# Very high-tech capsule



# Results?

- 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

Aalto University
School of Science

# Newest new: USA wants regain lead … SPARC !!

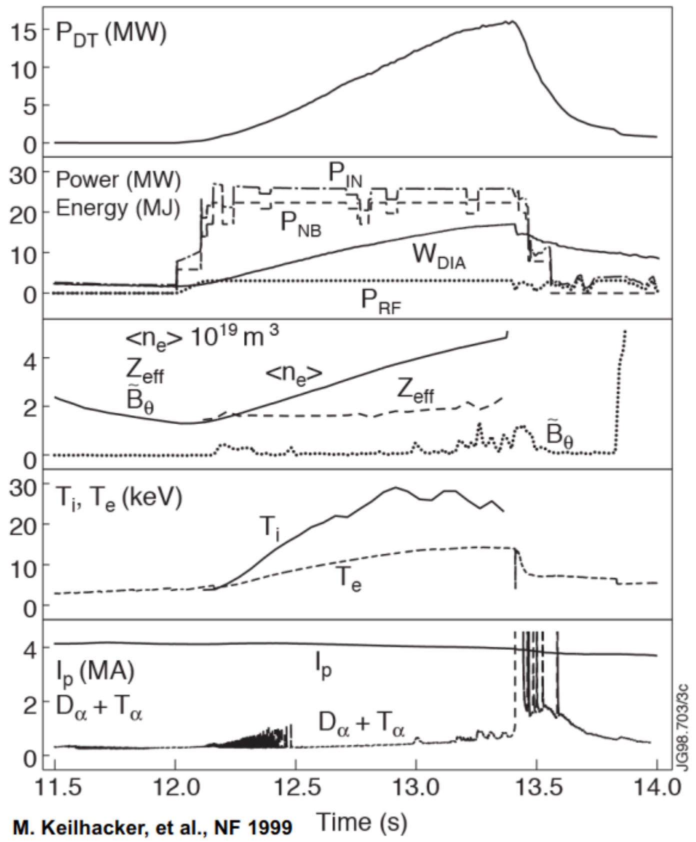

- Compact, high-field, DT burning tokamak at MIT
- Confine a plasma with net fusion energy
- Aggressive schedule: working in 15 years
- High-risk, high-gain project
- VERY similar to European TE Ltd but with more hype

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

# Fusion 'world record' 1997: 16.1MW

- Continuous increase in $P_{DT}$ with heating power (of total 25.4 MW) $\Rightarrow P_{fus}/P_{aux} \approx 0.64$ 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 2021*




M. Keilhacker, et al., NF 1999