Fusion devices – technology review

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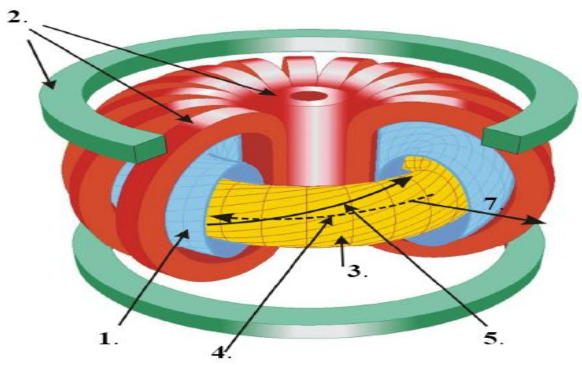
MŰEGYETEM 1782

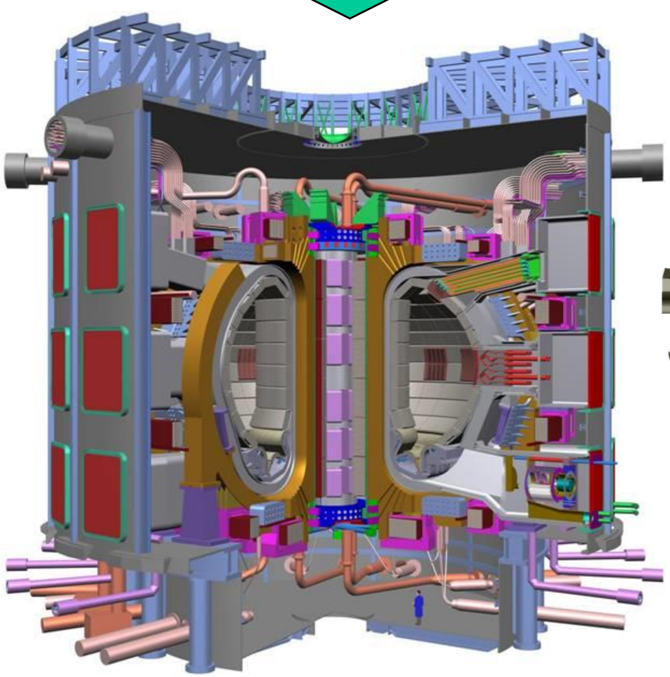
BME NTI

Provisional program

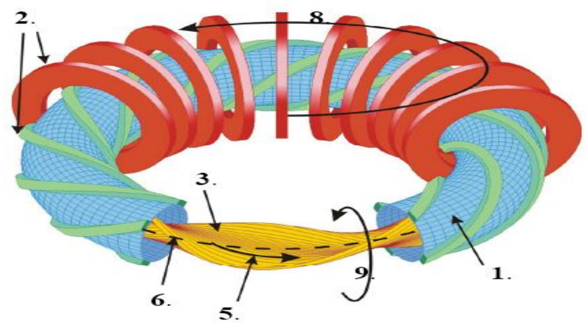
Date	Lecturer	Topic
15. February	Pokol	Theory review (fuel flow, magentic confinement, transport, tokamak, stellarator)
15. February	**Pokol**	**Technology review (vacuum, magnetic field, plasma heating, current drive, plasma diagnostics)**
22. February	Todd	How to build a tokamak
22. February	Todd	How to operate a tokamak
29. February	Pokol	Discussion of Tom Todd’s presentations
21. March	Pokol	Tokamaks and piches (history, JET, tokamak taxonomy)
4. April	Pokol	ITER (goals, structure, status)
11. April	Pokol	ITER – DEMO roadmap
18. April	Pokol	Middle-sized tokamak program
25. April	Pokol	Spheromaks, spherical tokamaks, US fusion program
2. May	Pokol	Far-East superconducting tokamaks
9. May	Pokol	Stellarators and linear devices (history, Wendelstein line, stellarator taxonomy)
23. May	Pokol ?	Wendelstein 7-X (goals, structure, status)

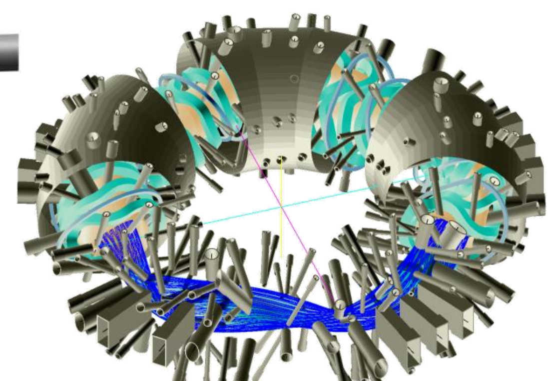
Tokamak





Stellarator





Wendelstein 7X

<u>Common subsystems</u>:

- Power supply
- Vacuum system
- Electromagnets
- Plasma heating
- Plasma fueling
- Plasma facing components
- Diagnostic systems

<u>Tokamaks</u>:

- Current drive technologies

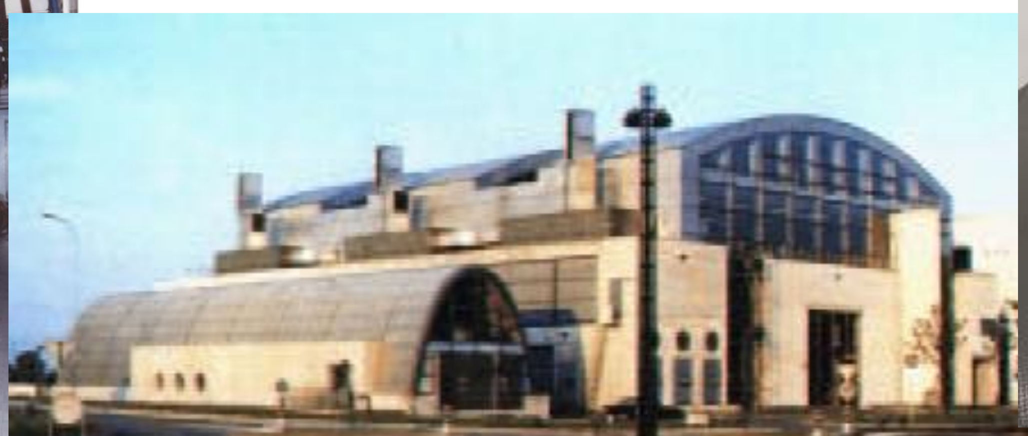
Power supply

Load:

- Short pulses, fast switching → transient load
- High power consumption: as high as 800 MW

Solutions:

- Power supply from grid
- Capacitor banks
- Large flywheel generators
- Modular flywheel system



Vacuum system

Estimate (vacuum):

Magnetic field: B_t < 10 T (superconducting magnets, mechanical stability)

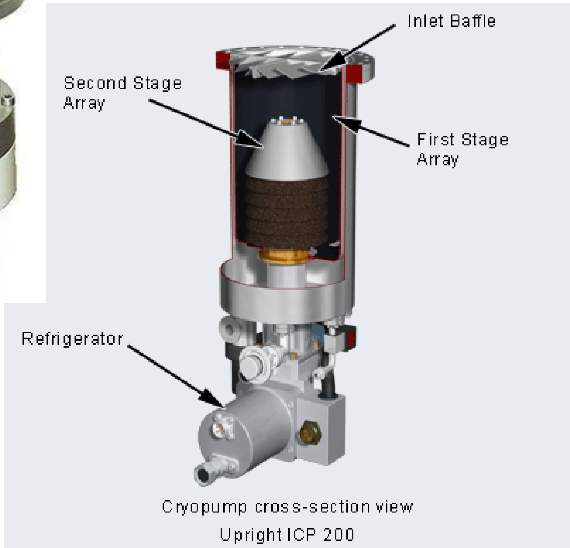
Maximum beta: β < 5%

→ p < $2 \cdot 10^6$ Pa (20 atm)

Temperature: $k_B T$ = 25 keV

→ n < $5 \cdot 10^{20}$ m^{-3} = 10^{-5} n_{air}

$$\beta = \frac{p}{B^2/2\mu_0}$$



Vacuum below 10^{-4} torr (1 torr = 133 Pa)

→ → two-step vacuum system :

Low vacuum pump, e.g. rotary

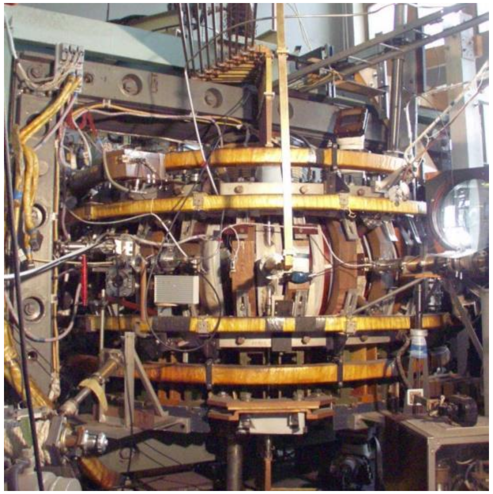
\+ turbo-molecular or cryogenic pumps

Vacuum chamber (liner):

- Rigid (pressure loads, electromagnetic loads)
- Thin and non-magnetic (for fast magnetic field diffusion)
- Bakeable at high temperature

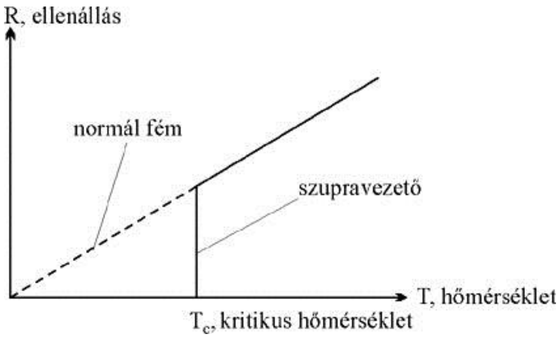
Electromagnets

Strong magnetic field (~ 5 T) requires strong current in toroidal field coils (~ 10 MA).



<u>Copper coils:</u>
- ~100 MW dissipated power
- „cooled” by heat capacity
- water (or liquid nitrogen) cooled

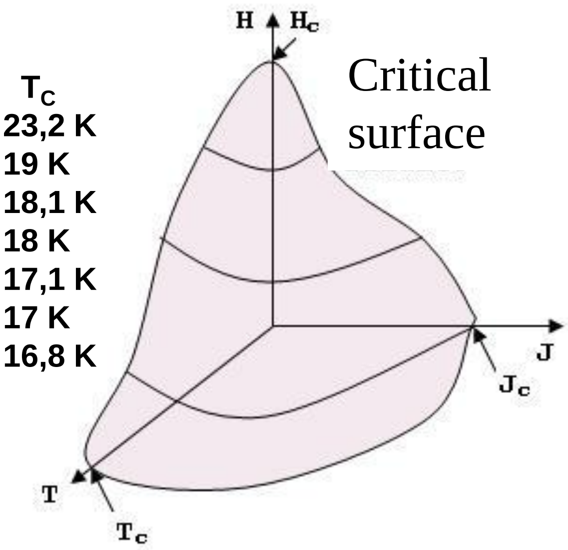
<u>Superconducting coils</u>:
- High temperature superconductors not available (yet)
- liquid He cooling
- Magnetic field stays up between discharges
- Limited change rate of magnetic flux



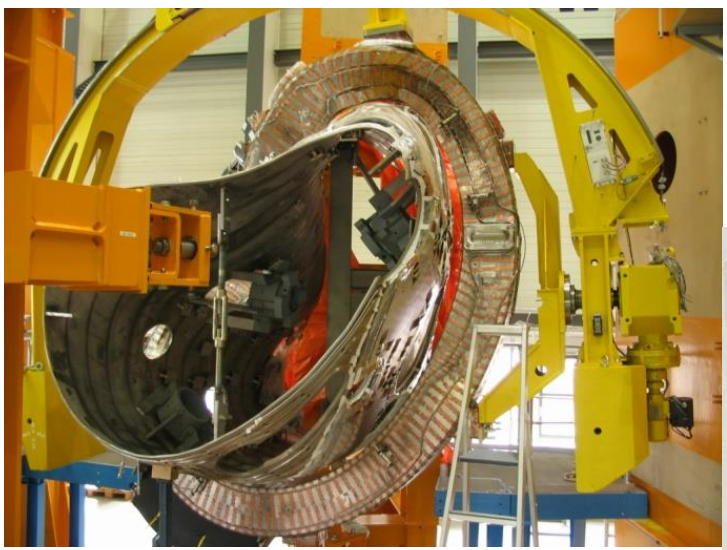
Superconducting coils

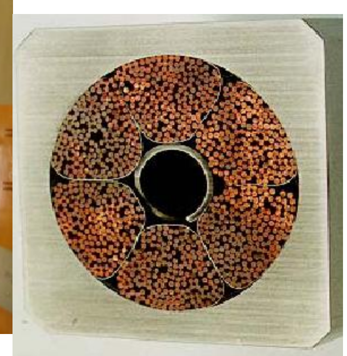
Limits of superconductivity:
- Critical temperature (T_c)
- Critical magnetic field (H_c)
- Critical current density (J_c)

	T_C
Nb_3Ge	23,2 K
Nb_3Si	19 K
Nb_3Sn	18,1 K
Nb_3Al	18 K
V_3Si	17,1 K
Ta_3Pb	17 K
V_3Ga	16,8 K

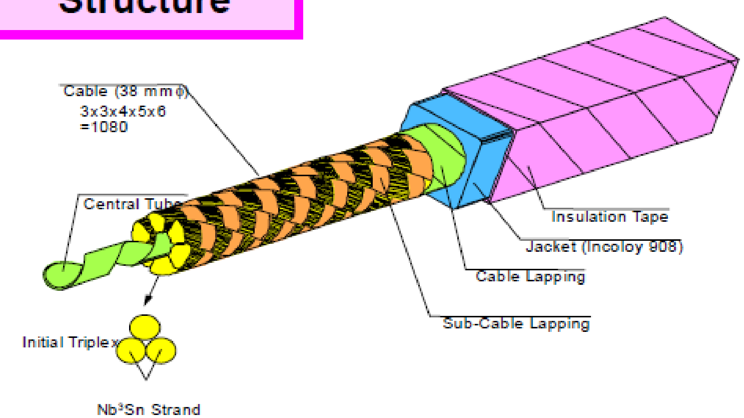


Internal cooling pipe
Super insulation + vacuum in cryostat





Conductor Structure



Ionization

DC breakdown:

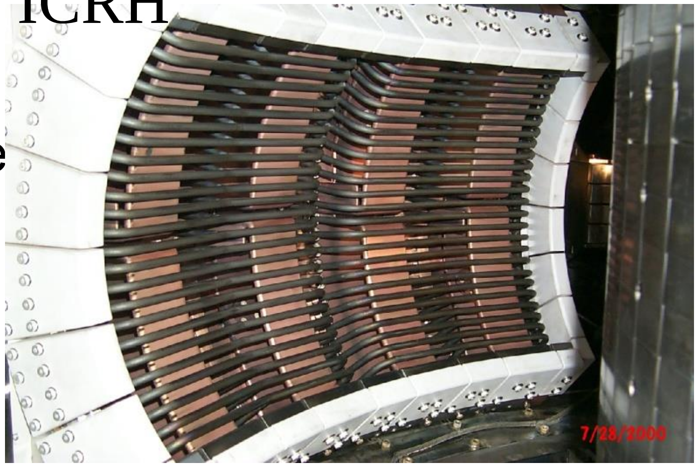
- In tokamaks!
- Consumes a lot of flux of central solenoid

Microwave breakdown:

- Always in stellarators
- Often in tokamaks
- Mostly with electron cyclotron resonance heating system (ECRH)

Plasma heating

ICRH



Ohmic heating

- In tokamaks!
- Power decreasing with increasing temperature

Neutral beam injection (NBI):

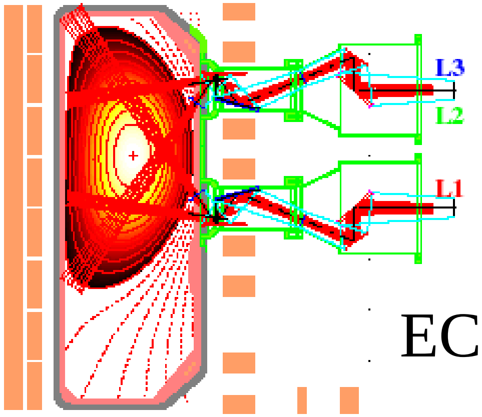
- Many beams usually, ~ 10 MW

Ion cyclotron resonance heating (ICRH):

- Radio frequency (RF) ~ 10 MHz, ~ 10 MW
- Loop antennas close to plasma

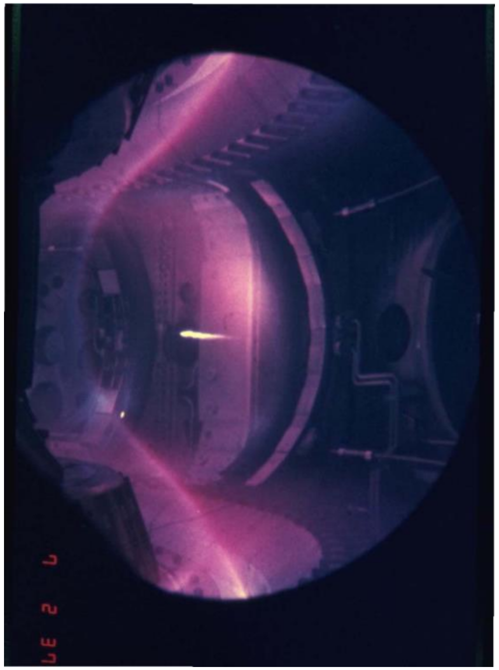
Electron cyclotron resonance heating (ECRH):

- microwave ~ 10-100 GHz, ~ 1 MW
- Optical wave propagation - mirrors
- Localized heating



ECRH

Fuel supply



<u>Gas puffing:</u>

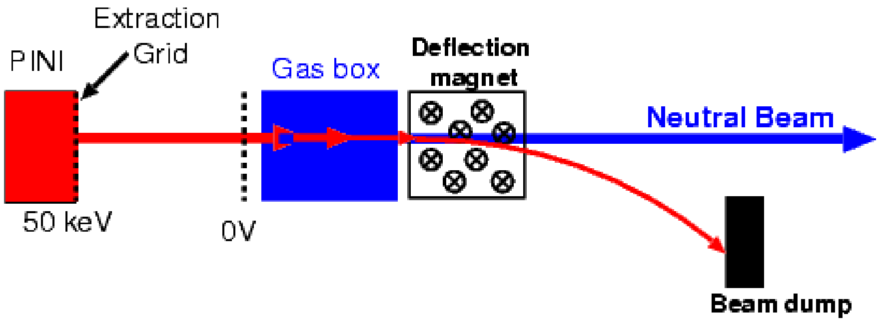
- Fuel supply of plasma edge – not effective

<u>Pellets</u>:

- Frozen hydrogen pellets (~cm)
- Acceleration with centrifuge, blower gun, ... ~1000 m/s
- Fuel supply of plasma centre – density peaking

<u>Neutral beam injection (NBI)</u>:

- Neutralizing an ion beam
- 50 keV – 1 MeV
- Charged particle equivalent current ~10 A
- Fuel supply of plasma centre



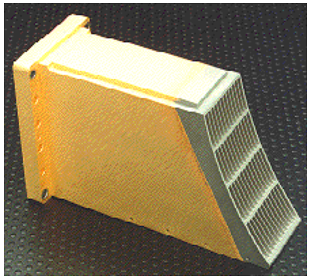
Current drive (in tokamaks)

<u>Transformer coils</u>: $\Delta\Phi/\Delta t = \mathrm{rot}\, E = U_{loop} = R_{plasma} \times I_p$

- Finite flux change in central solenoid (primary transformator coil)

<u>Lower hybrid current drive</u> (LHCD):

- Starting tokamak demonstrated



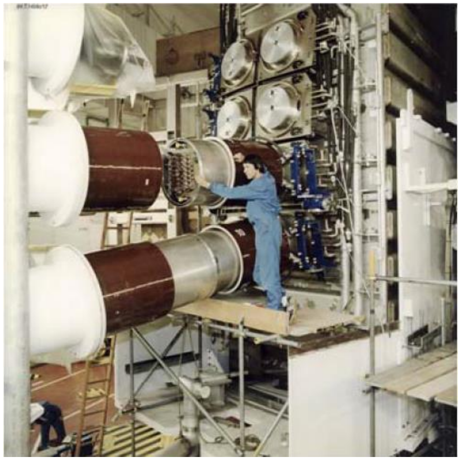
Microwave lower hybrid antenna

<u>Electron cyclotron current drive</u> (ECCD):

- non-perpendicular wave launch
- Local current drive → fine control of current profile

<u>Neutral beam injection</u> (NBI):

- Toroidal launch
- High energy ions in the plasma through charge-exchange
- High energy ions drag the electrons



<u>Bootstrap current</u>:

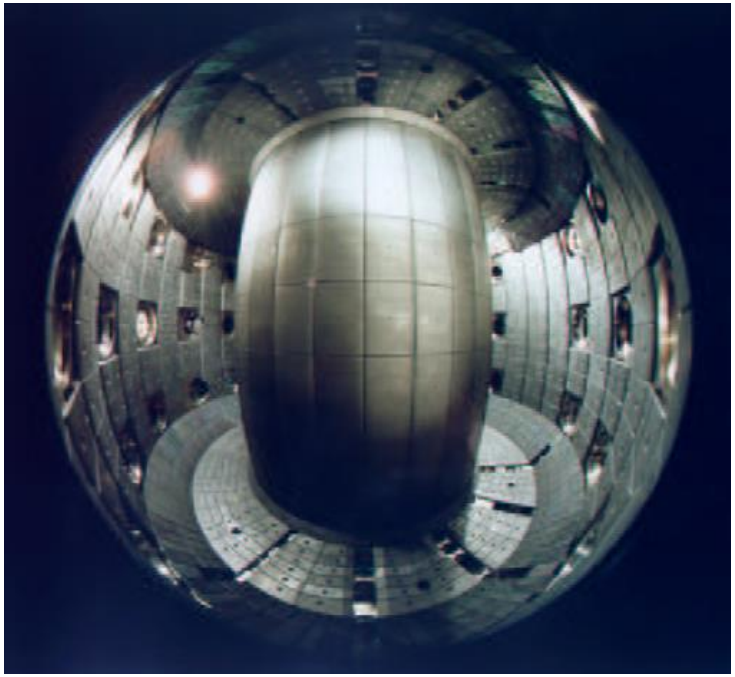
- Neoclassical toroidal plasma current, ~ grad*p*
- Internal transport barriers → bootstrap current at plasma centre
- 100% bootstrap tokamak plasma demonstrated (TCV)

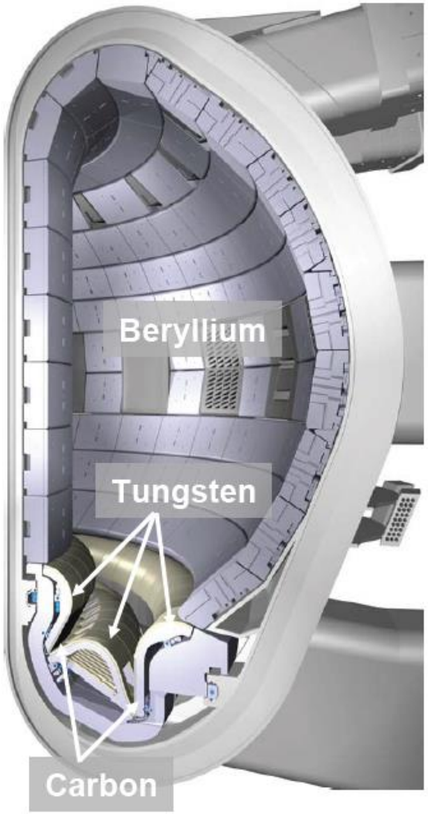
Plasma facing components - first wall

High vacuum → avoid adsorption of gas molecules on wall surfaces

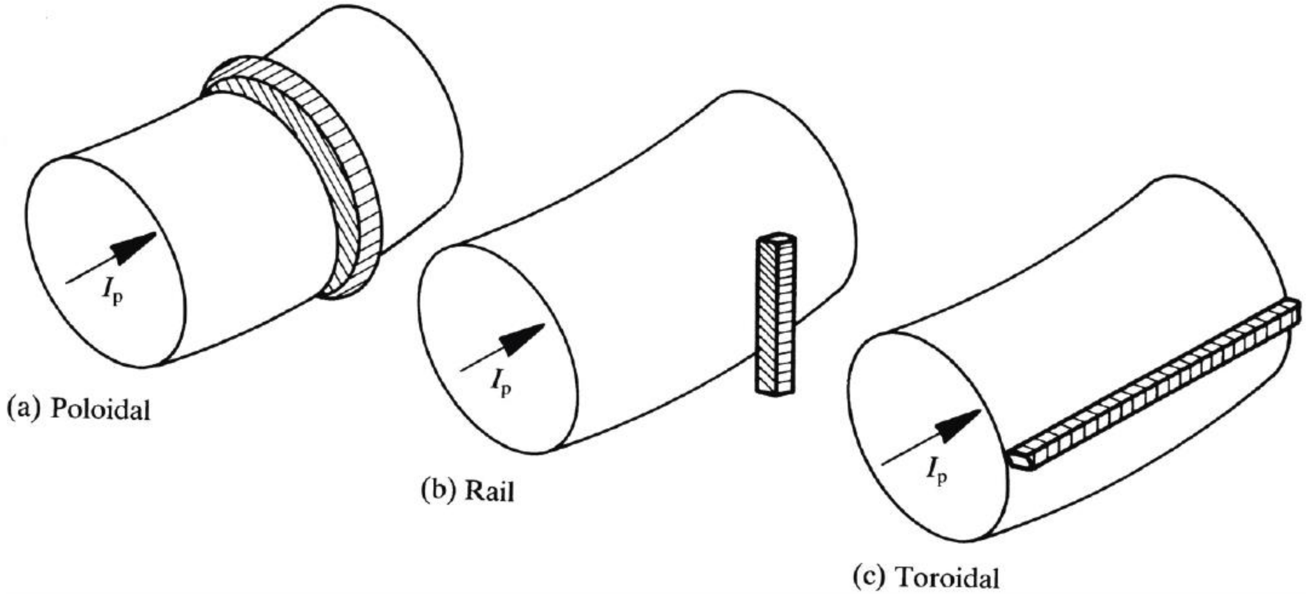
Wall conditioning: baking, leaning by ion bombardment (Glow-discharge, conditioning plasma discharges)

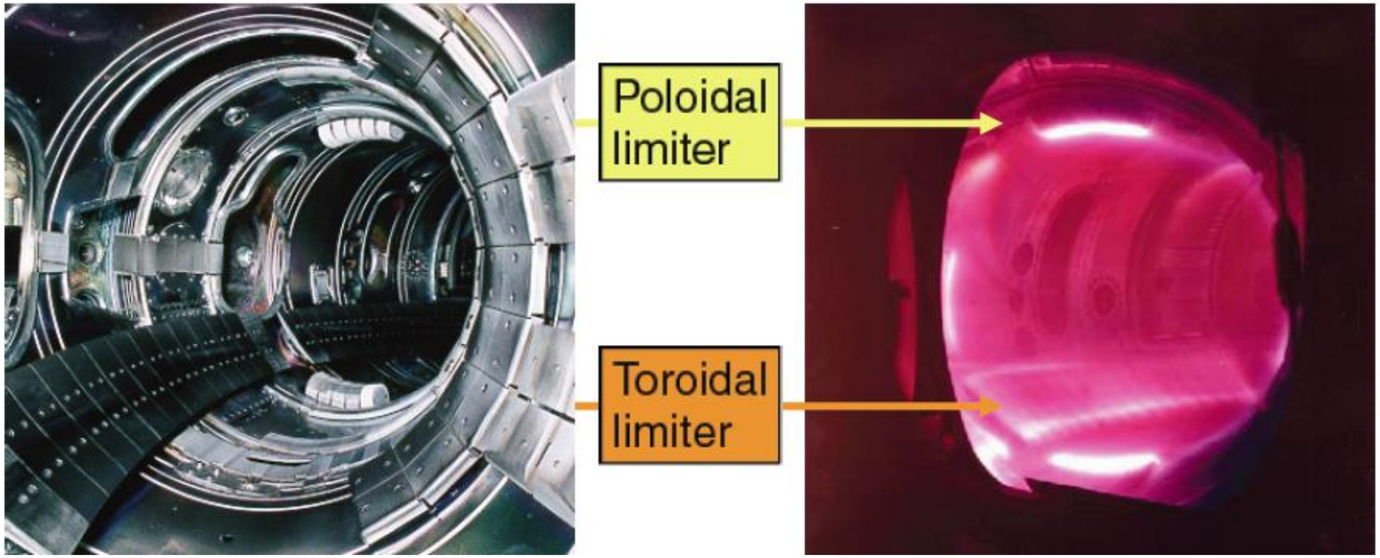
Special first wall materials: carbon (CFC), tungsten, beryllium, molybdenum, boronization, …



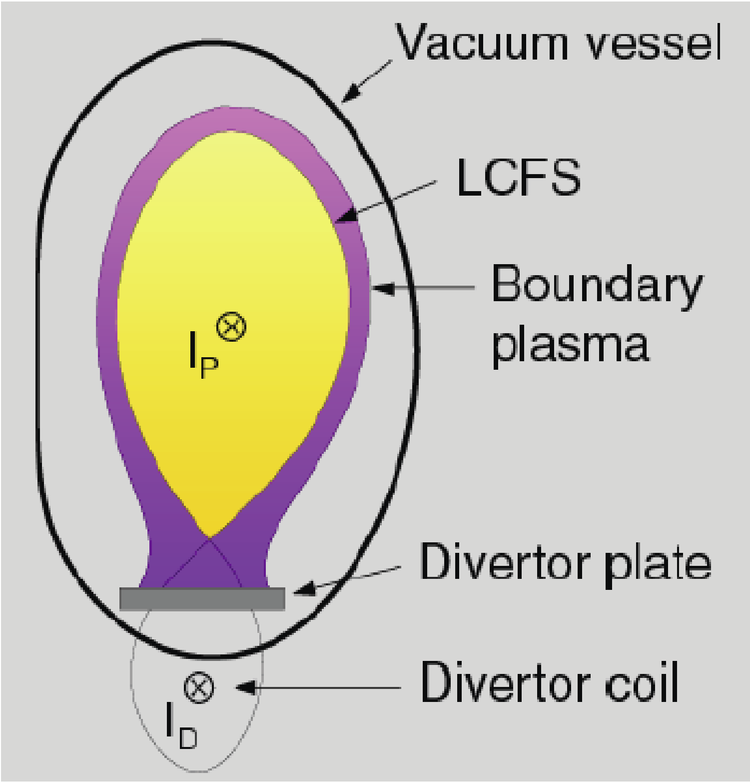


Limiters

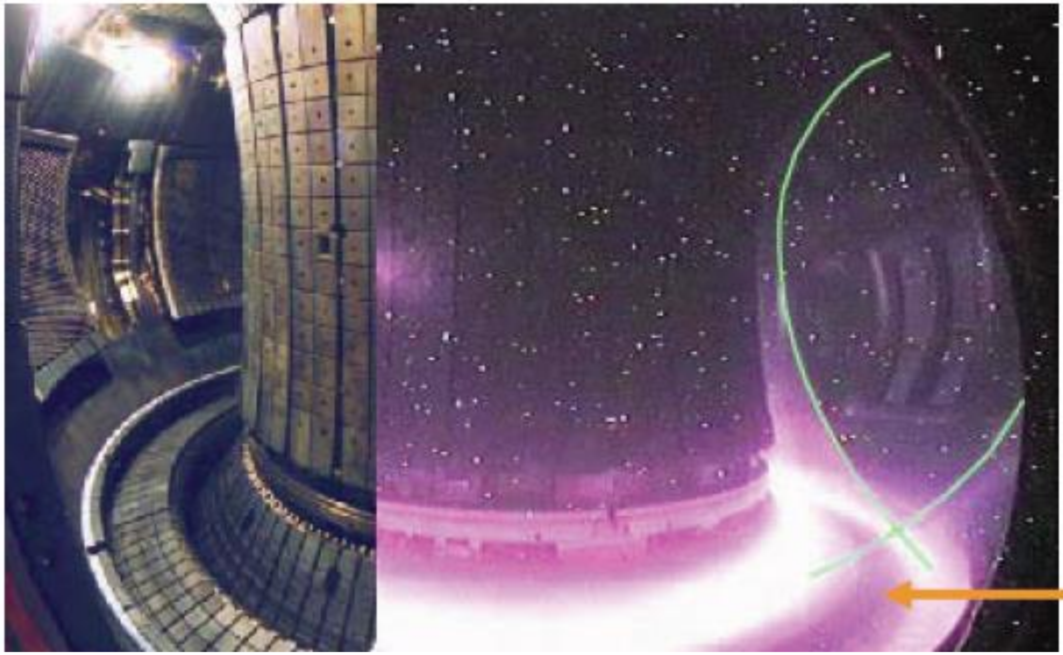

I_p
(a) Poloidal
I_p
(b) Rail
I_p
(c) Toroidal


Poloidal limiter
Toroidal limiter

Divertor



Primary plasma-wall contact far from confined core – transport along open field lines.



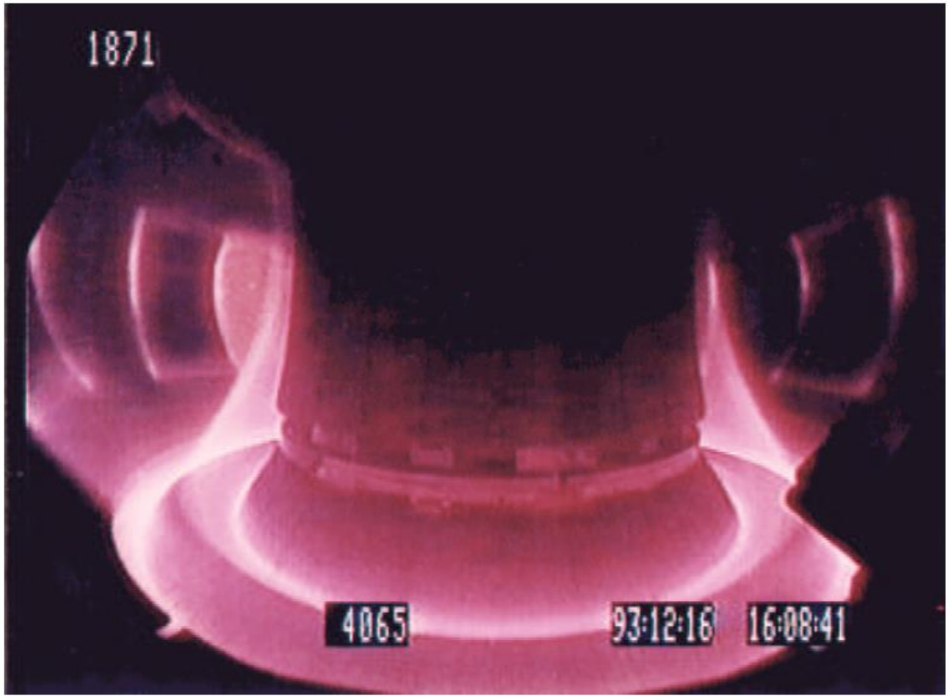
The divertor in ASDEX Upgrade

Attached and detached plasma

Attached: direct plasma-wall interaction

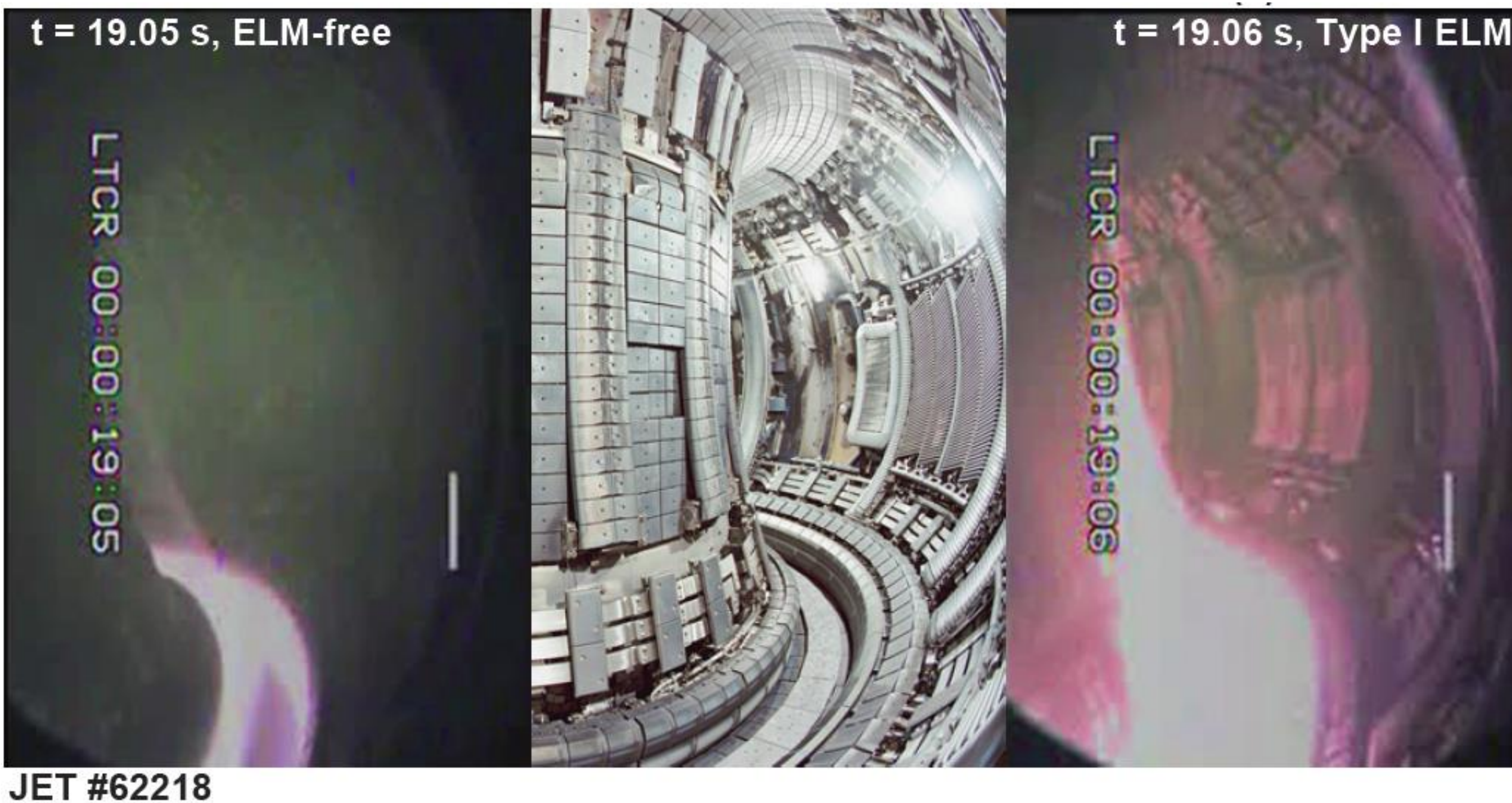
Detached: high density local (private) plasma radiating the power

ASDEX-Upgrade attached plasma

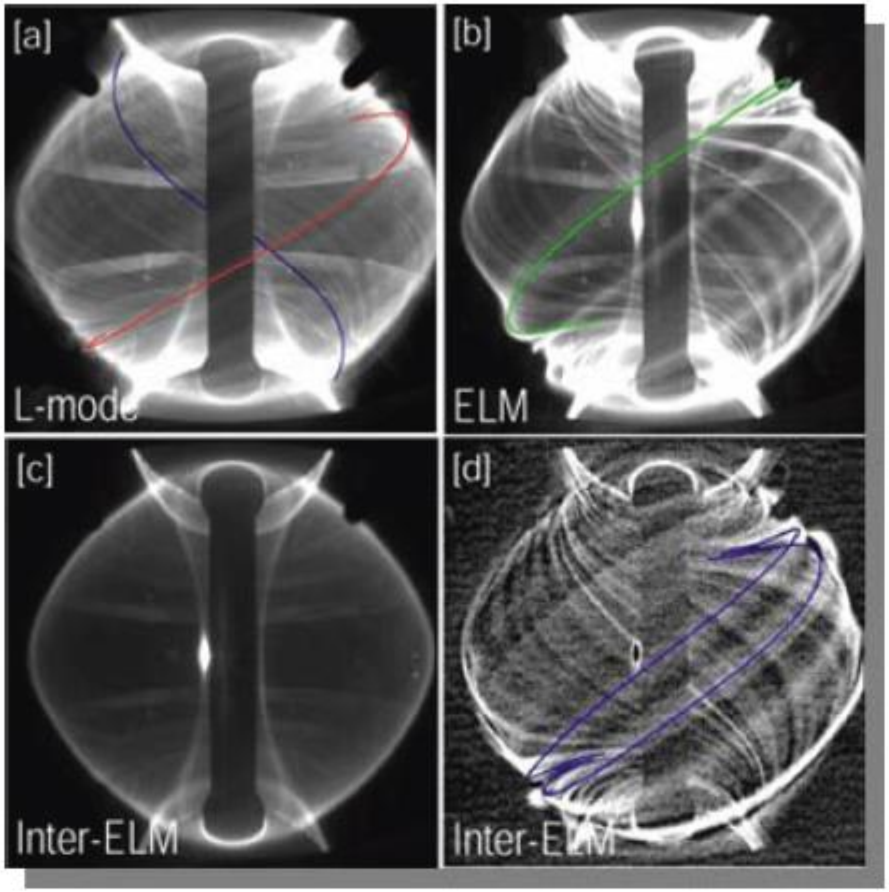


ASDEX-Upgrade detached plasma

Wall loads during ELMs

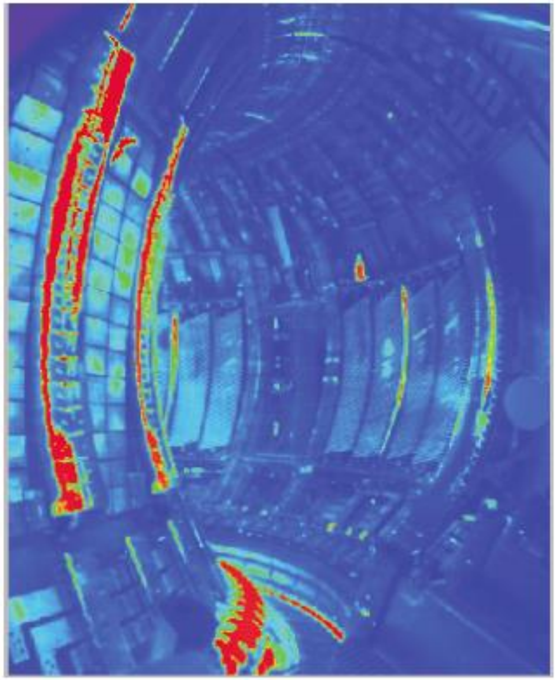


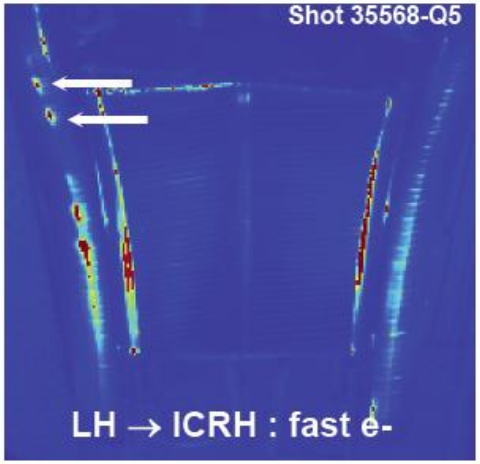
Other localized wall loads



filaments (MAST)

disruptions (JET)



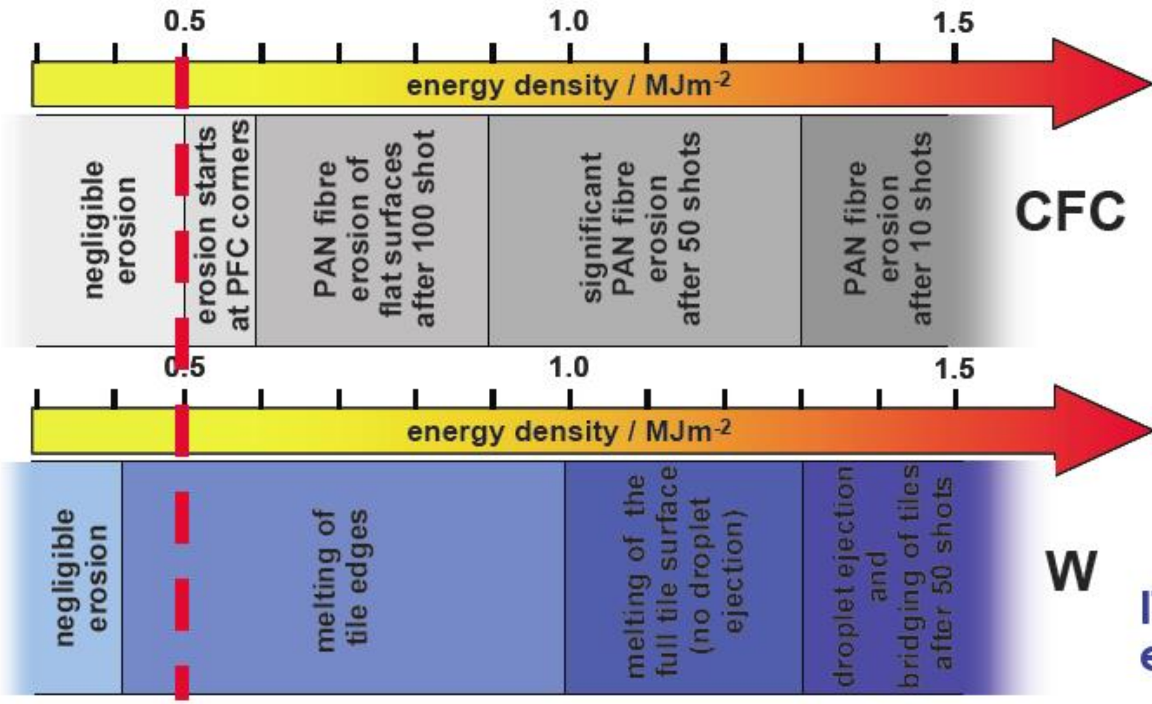


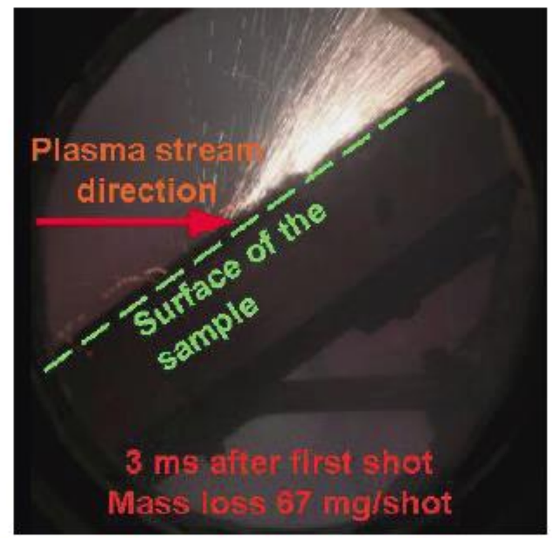
Fast particle beams

Wall material

<u>Criteria for choosing wall material</u>:

- **Effect of heat transients**
- **Erosion and re-deposition** (with hydrogen isotopes!)
- **Plasma dilution with impurities**
- Further practical properties

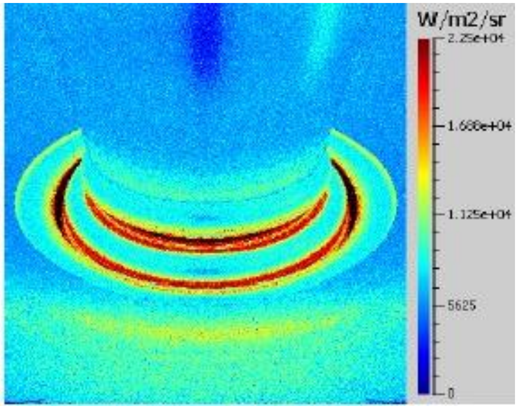




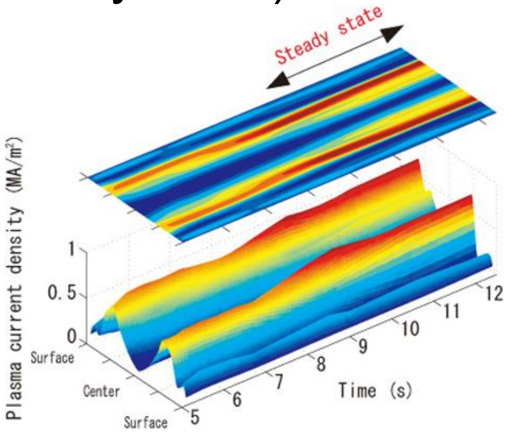
ITER : 0.5 MJ/m^2 **max allowed ELM energy load**

Diagnostics – purpose

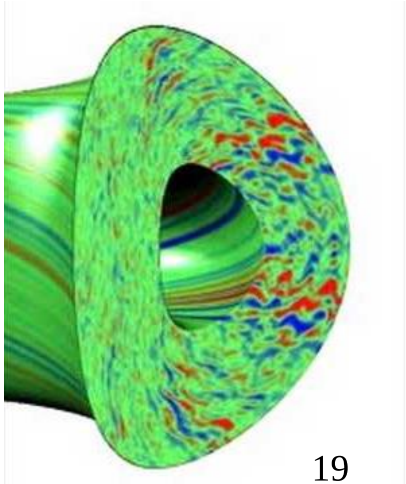
1a: <u>Basic control and device protection</u>:
- Plasma position
- Heat load on plasma-facing components
- B_t, I_p, n_e, total pressure (stability limits)
- ...



1b: <u>Fine control</u>:
- Current profile
- He density
- ...



2. <u>Performance evaluation, physics understanding</u>:
- T_e, n_e fluctuations
- Radial electric field
- …



Diagnostics – methods

Passive diagnostics

Magnetic coils (integral measurement)

Passive spectroscopy (line-integrated measurement)

Neutral particle analyzator (integral measurement)

Thermography (local measurement)

Electron cyclotron emission (local measurement)

Active diagnostics

Interferometry (line-integrated measurement)

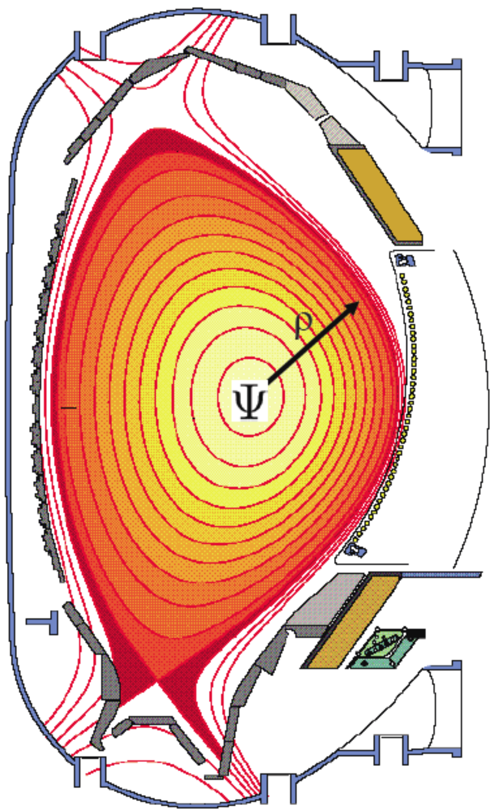
Reflectrometry (local measurement)

Thomson scattering (local measurement)

Atomic beam diagnostics (local measurement)

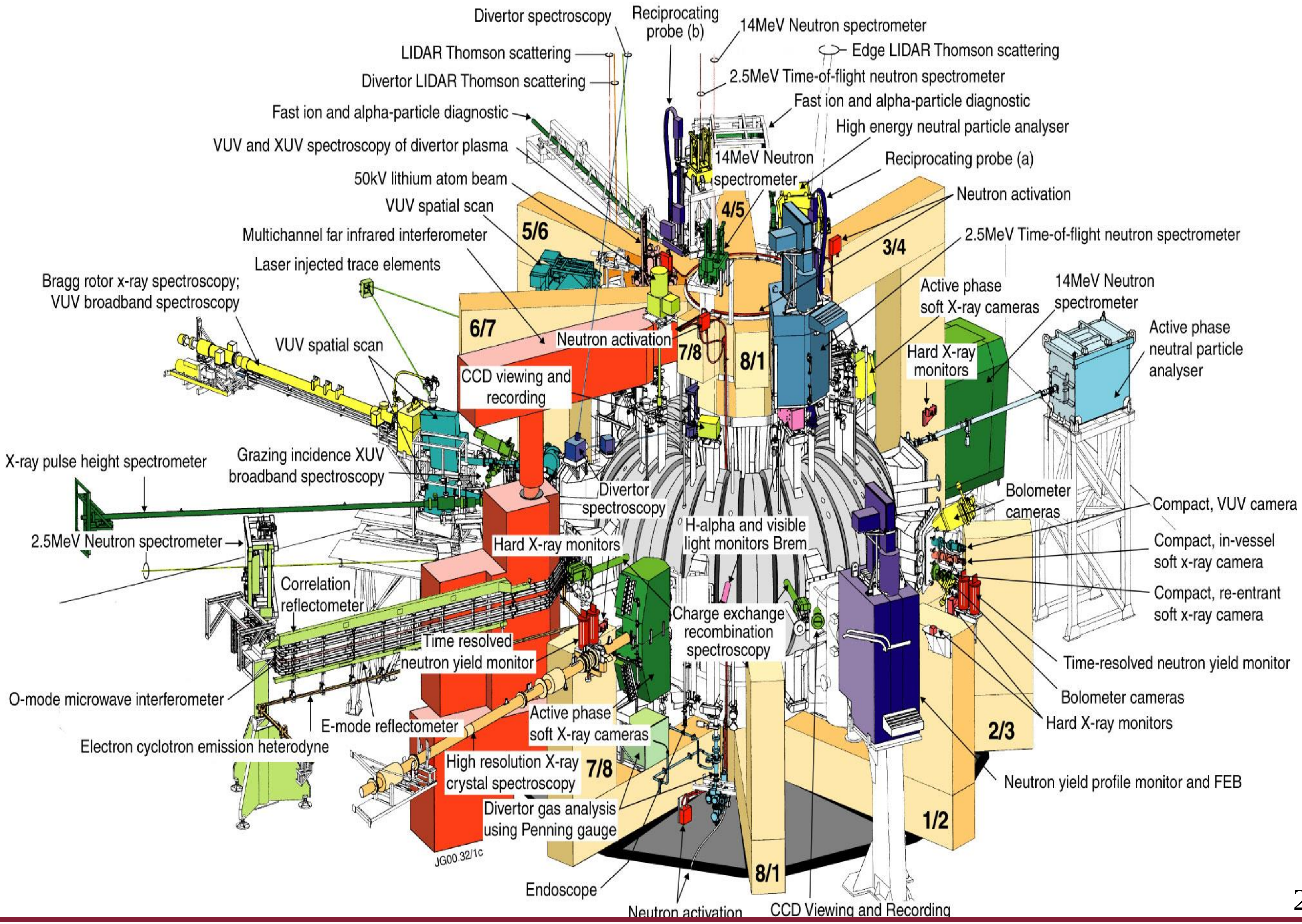
Langmuir probe (local measurement)

...



Quasi-stationary physical quantities can be extended along flux surfaces!

JET diagnostic systems



Summary

<u>All magnetic confinement fusion devices have the same types of subsystems:</u>

- Power supply
- Vacuum system
- Electromagnets
- Plasma heating
- Plasma fueling
- Plasma facing components
- Diagnostic systems
- Current drive (in tokamaks)

<u>Similar technologies may be extremely diverse in details.</u>