From physics to design
(Conceptual design)

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The previous talk

- Working with plasmas in fusion magnetic devices imposes to dealing with a high power transition layer, the so called scrape off layer
- The heat fluxes are very high (actually at the limit of what current technologies allows)
- In addition to the plasma load, multiples other aggressions tend to burden the components (localized loads caused by supra-thermal particles, neutrons, transient loads
- The plasma facing materials are key to a controlled plasma surface interaction, and their choice is very limited

The topics of this talk

- A short history (3 slides)
- How organize the components ? (5 slides)
- Wall shaping (4 slides)
- Power deposition, heat flux peaking (5 slides)
- Some technical insights into component design (4 slides)
The first plasma facing components: Plasma "limiters"

Research on controlled nuclear fusion and the physics of high temperature plasma in the USSR, L.A. Artsimovitch Plasma Physics, 1965, Vol.7 pp 477 to 489: Details of Tokamak principles

"to minimize the interaction between the plasma and the surface of the [inner vessel],

**a diaphragm is inserted inside the liner to restrict the cross section of the plasma pinch.**

An inconel limiter in TFR

Surface is melted due to plasma contact (A. Grosmann)

TFR 1973-1984

Inner vessel of TFTR 1982-1997
Decades 70 – 80: increase limiter surface to reduce the heat load

- Localized / large area
  - In Tore Supra: inner first wall versus mushroom limiter
- Poloidal limiters: rings, guard limiters, partial limiters
  - TFTR inner bumper, "Poloidal limiters" on JET
- Toroidal:
  - ALT-II at TEXTOR
  - Pump toroidal limiter at Tore Supra

Local outboard limiter in Tore Supra (0.5 m²)

Inner first wall in Tore Supra (25 m²)
1982: The divertor configuration increases the isolation of the central plasma $\Rightarrow$ confinement is improved

- Keep central plasma far from the area where it interacts with the wall
- Keep impurities far from the confined plasma

Consequences for the PFCs

- Increased geometrical complexity

Decade 90: divertors become the standard for the high power plateau phase

*But there are still many limiters in every device...*
Main role of the components

- Avoid contamination of the plasma by wall materials & Avoid damaging the vessel
- Focus here: how to handle the heat fluxes
  - High heat flux components (> 5 MW/m²)
  - Medium heat flux components (0.5 to 2 MW/m²)
  - Low heat flux components (< 0.1 MW/m²)
- Put the right components at the right place

⇒ Wall organisation
How organise the components?

A series of localized components

A large inner wall

A serie of poloidal limiters

A toroidal component

Component = Limiter or divertor

- Basically, all the vessel needs protection
- Localizing the plasma surface interaction usually also allow to control it.

- Combinations are often used
Main Component / Secondary components

• A large component (or a set of similar components) is often designated as main component
  – Able to sustain all the SOL power
  – Allows to keep all secondary components deeps in the SOL, hence to develop a large SOL which is favourable regarding power exhaust

  Examples
  – Toroidal limiters in TS, ALT-II at Textor
  – The axi-symmetric divertor in JET, ASDEX, JT-60
  – TFTR inner bumper

• The other components are designed with respect to the main component
  – For residual power (lower power)
  – Or dedicated to one event (ex. fast particles)

  Examples
  – Antenna protections
  – Poloidal limiters at JET
Illustration of secondary components in Tore Supra

- Wall panels
- Ripple losses protections
- Lateral protection for lower hybrid launcher
- Ergodic divertor neutralisers
- Diagnostic Protections
Protection surface pavements some analogies

- Account for the fact that the heat flux will arrive on both sides
- Make use of the shadow to protect the leading edges
- Avoid near perpendicular surfaces to the flux tubes, especially close to the LCFS
Cosine law

- The heat flux depends:
  - On the depth in the scrape off layer (distance to the last closed flux surface)
  - On the incidence angle (angle of the magnetic field lines to the component surface)

\[ \varphi = \varphi_0 \cdot e^{-\frac{\delta}{\lambda_q}} \cdot \sin \alpha \]

- A simplified model, not the actual reality
  - Non exponential scrape off layer
  - Cross field heat flux
  - Sheath effects
  - Larmor radius effects

- Still today, the best tool for the engineers
  - contains most of the well admitted physics "smallest common denominator"

Incline the tile to reduce the heat flux

⇒ Requires more vessel surface
Component shaping

- A generic shape: the "roof like" tile and its cousins (dome etc...)

Textor ALT-2 (FZJülich)

Surface shaping
- stay under the maximum heat flux allowed by the technology (0.1 ; 1 ; 5 MW/m²)
- make best use of the vessel space

A tile of the wide poloidal limiter from JET (E. Villedieu)
The constant flux problem

Solving this to a "constant heat flux" gives the following differential equation:

\[ C = \exp \left( - \frac{y}{\lambda_{\text{design}}} \right) \frac{dy}{dx} \]

Geometrical profile of constant heat flux over 2 mm (for \( \lambda = 1 \) mm)

Application for a PFC element for the ITER Faraday shield

"technically manufacturable by the industry"
Mutual interactions between components

In other words: the magnetic connections

Successive limiters project their shadow on following limiters

⇒ Only a small fraction of the surface is wetted by the plasma

Heat flux deposition with shadowing on the inner wall guard limiter of JET (M. Firdaous)

놀이, a fraction of the usable surface is lost, peaking factor is increased

😊 the shadow can be used to protect high incidence surfaces, attachments

+ tricky effects: re-deposition of eroded material, self-shadowing effects
Openings : Gaps and Ports

• Gaps are needed
  – Allow component thermal dilatation, hence reduces thermal stresses
  – Reduces the size of possible electric loops, hence electro-mechanic loads
  – Access to attachments (bolts)
  – Allow adjustment
  – Lets beams or diagnostics signals pass through the wall

• But they require a dedicated analysis
  – Slopes, fillets
  – Edge profiling
  – Thermal analysis
  – Retention ?

  Toroidal gap
  0.5 mm

  Poloidal gap
  1.2 mm

⇒ Caring for misalignments
• Current devices : 0.5 mm
• Iter : 5 mm

Port openings in DIII-D

Diagnostic slot in the TPL of Tore Supra
Ok, but let's talk about numbers.

How many MW/m² ?
The simple example of Tore Supra

\[ P = 15 \text{ MW} \]
\[ B_t = 4 \text{ T} \]
\[ I_p = 1 \text{ MA} \]
\[ \lambda_0 = 10 \text{ mm} \]
\[ a = 0.75 \text{ m} \]
\[ r = 2.4 \text{ m} \]

\[ \alpha = \arctan (0.28/4) = 4^\circ \]

\[ B_p = \frac{\mu_0 I_p}{2 \pi a} = \frac{4 \pi \cdot 10^{-7} \cdot 10^6}{2 \pi \cdot 0.72} = 0.28 \text{T} \]

\[ P = 2 \cdot (2 \cdot \pi \cdot R_p) \cdot \lambda_q \cdot \phi_0 \cdot \sin \alpha \]

\[ \phi_0 = \frac{P}{2 \cdot (2 \cdot \pi \cdot R_p) \cdot \lambda_q \cdot \sin \alpha} \]

\[ = \frac{15 \cdot 10^6}{4 \cdot 3.14159 \cdot 2.4 \cdot 0.01 \cdot 0.07} = 710 \text{ MW/m}^2 \]

\[ \int_{\delta=0}^{\delta=\infty} e^{-\frac{\delta}{\lambda_q}} d\delta = \lambda_q \]

Heat flux decay length

Pitch angle

\[ q_{sep}^\parallel = 950 \text{ MW/m}^2 \]

NB SOL Iter @ 100 MW
Effective area, peaking factor

- Designed for 15 MW @ 10MW/m²
- TPL area: 7.5 m²
- For 7.5 MW discharges
- Mean heat flux: 1 MW/m²
- Heat flux is peaked
  => 5 MW/m²
  (+/- depending on conditions)
- Peaking factor is 5

*Or in other word*
- Effective heat exhaust area is 1.5 m²

Calculated heat flux on the TPL @ 1.5 MA with 50 cross field heat flux
Power balance in a divertor tokamak

- $f_{\text{rad}}^{\text{main}}$ power fraction radiated in the main plasma
  Distributed between
  - A part coming from the core
  - A part coming from the SOL and the edge
- $f_{\text{rad}}^{\text{div}}$ power fraction radiated in the divertor
- Accounting for the asymmetry between inner and outer legs

\[
\begin{align*}
  P_{\text{heat}} & \rightarrow 90\% \quad P_{\text{abs}} \\
  10\% & \quad \text{shine through re-ionization} \\
  P_{\text{rad}}^{\text{core}} & \rightarrow 0.5P_{\text{rad}}^{\text{main}} = P_{\text{rad}}^{\text{core}} = P_{\text{rad}}^{\text{SOL}} \\
  P_{\text{rad}}^{\text{main}} & \rightarrow P_{\text{rad}}^{\text{main}} \\
  P_{\text{rad}}^{\text{SOL}} & \rightarrow P_{\text{SOL}} \\
  P_{\text{SOL}} & \rightarrow P_{\text{div}}^{\text{up}} \\
  2/3 & \quad P_{\text{div}}^{\text{out}} \\
  f_{\text{rad}}^{\text{div}} & \quad P_{\text{rad}}^{\text{div}} \\
  1/3 & \quad P_{\text{div}}^{\text{in}} \\
  f_{\text{rad}} = f_{\text{rad}}^{\text{main}} + (1-f_{\text{rad}}^{\text{main}}) f_{\text{rad}}^{\text{div}} \\
  P_{\text{tar}}^{\text{out}} & \rightarrow P_{\text{tar}}^{\text{in}} \\
\end{align*}
\]

(S. Sakurai – JAEA)
Divertor, cont.

- Make best use of plasma expansion
- Still incline the targets

\[ \text{Area} \sim 4\pi R \lambda_q \left( \frac{B_\theta}{B} \right)_{u} \sim 0.2m^2 \]
\[ \lambda_q = 5 \text{ mm} \]
\[ q_{||,u} \sim 500 \text{ MWm}^{-2} \]

Magnetic flux expansion
\(~(B_\theta/B)_{u}/(B_\theta/B)_t \sim 4\) for ITER outer divertor \to low field line angles at strike points (~3°)
\[ \text{Target tilting in poloidal plane} \] (\(\alpha \sim 25°\) for ITER outer target)

\[ \text{Area} \sim 4\pi R \lambda_q \left( \frac{B_\theta}{B} \right)_{u} / \sin(\alpha) \left( \frac{B_\theta}{B} \right)_t \sim 3.0m^2 \]
\[ q_{\perp} \sim 16 \text{ MWm}^{-2} \]

- Max. steady-state power flux density permitted at ITER divertor targets: \(q_{\perp} \leq 10 \text{ MWm}^{-2}\)
- Magnetic and divertor geometry alone cannot reduce the power to tolerable levels
- Most of the parallel power flux must be prevented from reaching the plates \(\to\) divertor detachment and high radiative loss

(G. Counsell, R. Pitts)
Heat flux modelling: toward the integration of tools from the design office and the engineers and physicists

Example of the Iter like wall at JET

Design the wall for a defined number of plasma contacts

DO models CAD (Catia V5)

Simplification details, meshing

Export in FEM code

Magnetic configuration (Proteus)

CFPFLUX

3610003: natural elongation
3610004: standard limiter plasma
3610005: high elongation
3610006: most extreme limiter plasma
3610007: late phase limiter configuration
Localized heat loads

- Time peaking
  - Elms (Edge localised mode)
  - Disruptions
  - Electron runaway
  - VDE (Vertical displacement event)

- Geometrical peaking
  - Marfes
  - Electron ripple losses (LH)
  - Electron runaway
  - Shine through, port re-ionization (IDN)
  - Near field accelerated electrons (LH)
  - Ion ripple losses (FCI) ⇔ large orbit losses
  - Drift electrons (LH)
  - Sheath effect of ICRH antenna frame

- A variety of events
- Design necessitates knowledge of:
  - Location: position and extend
  - Power
  - Peak heat flux

Example in Tore Supra

Peaked heat losses from RF heating in Tore Supra

- LH heating
  - fast e- ripple losses
    - type III
  - type I fast e-
  - type II fast e-

- ICRH heating
  - fast ion ripple losses
  - Sheaths effects on antenna

IR view of the TPL during #29898 Supra thermal electrons on the TPL
Double the plasma load...

Physical model helps... when available
Main principles of plasma facing component design

Heat flux pattern

Materials

Tile
Either compatible with the plasma (C, Be) or with a very low sputtering yield

Hold the tile
Technologies, manufacture

Cool the tile

Analyses
Thermo-mechanical
Thermo-hydraulical
Electro-mechanical

Test, qualification, Q&A, Project management
## Modular conception: different scales

<table>
<thead>
<tr>
<th>Component scale</th>
<th>Element scale</th>
<th>Tile scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>The pumped toroidal limiter of Tore Supra</td>
<td>574 elements to complete the limiter</td>
<td>21 tiles on an element</td>
</tr>
<tr>
<td>A wide poloidal limiter of the Jet Iter like wall</td>
<td>23 tiles to complete one limiter</td>
<td>7 blocks per tile</td>
</tr>
</tbody>
</table>
How to cool: after the pulse? Or on line?

• **The historical concept:**
  • Stores the heat in the tile during the discharge, then evacuate it by radiation toward a circuit with a reduced heat transfer capability
  • Main thermo-physical property: \(C_p\) (J/KgK)
  • Only for short discharges
  • Problem: hold the tile without melting the bolt (carbon or molybdenum bolts can be used: 2400°C)
  • Machines: JET ASDEX, DIII-D, TEXTOR…

• **The current concept**
  • Evacuate the heat toward a coolant as rapidly as it arrives
  • Main thermo-physical property: the thermal conductivity: \(\lambda\) (W/mK)
  • Allows steady state regime
  • Problem: thermal gradient builds up, along with high mechanical stresses
  • Machines: TS, LHD, EAST, W7X, ITER…

**Bolt font**: machines in use in 2007

Bolted tiles concepts for TFR (1970)

A cross section through the large area inner bumper of Tore Supra (Brazed by Plansee, 1996)
The main concepts of actively cooled components

Flat tile

- Plasma compatible material
- Interface material
- Cooling channel
- Structural material

- ☺ flat interface easier to manufacture
- ☺ easier to control
- ☺ easily reparable
- ☹ high singularity on the free edge

Monobloc tile

- ☺ The tile remain even when the bond fails
- ☺ low mechanical stresses
- ☺ low bond temperature
- ☹ still some stresses at the ends
- ☹ difficult to control
- ☹ difficult to repair

But also: saddle type concept

Intermediates Characteristics
Conclusion

Good luck

The Inner first wall of Tore Supra in 1999 with some tiles that see some heat  #28353

And thanks for your attention