PPCS Reactor Models

9th Course on
Technology of Fusion Tokamak Reactors

International School of Fusion Reactor Technology - 2004

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Overview

Fusion Tokamak Reactors: WHY ?

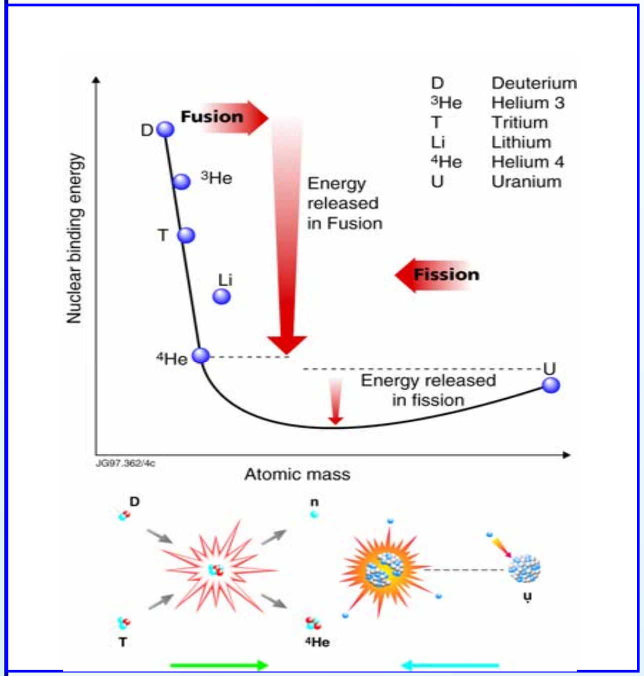
PPCS Reactor Models

Key issues for DEMO/Reactors

Conclusion

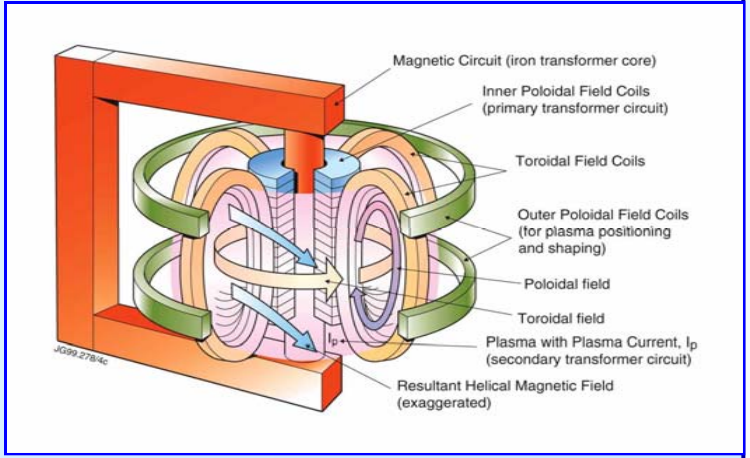
Tokamak Fusion Reactors WHY ?

Fusion Machines



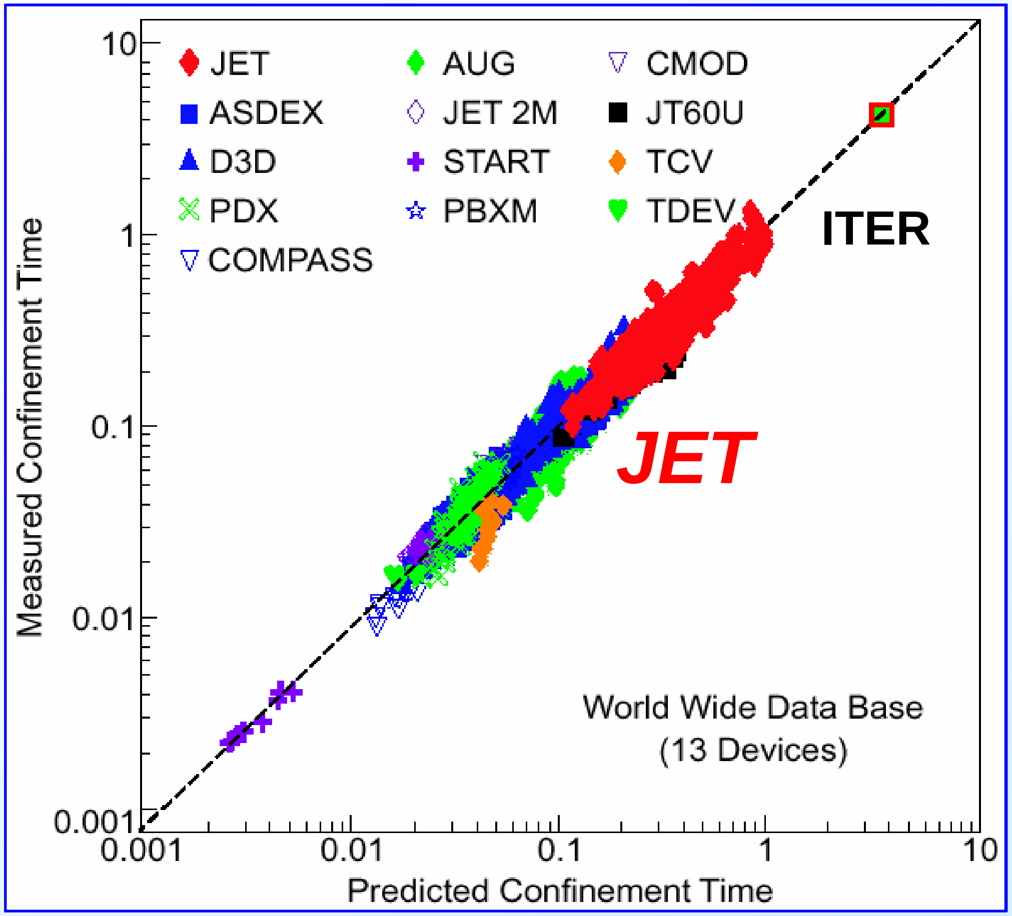
Different magnetic configurations are possible: tokamaks, stellarators, reversed field pinches and spherical tokamaks.

Tokamaks have been the most successful machines up to now.



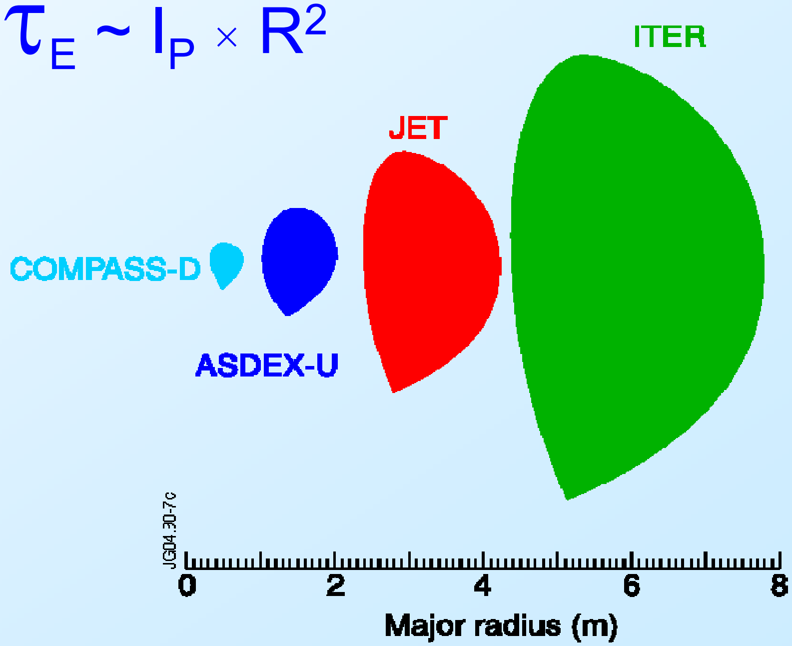
The largest fusion machines built to date are tokamaks (JET, JT60, TFTR), the next step machine (ITER) will be a tokamak and most reactor studies assume a tokamak configuration.

Tokamak Success Story



$\tau_E = W_{th}/P_{LOSS}$

$\tau_E \sim I_P \times R^2$



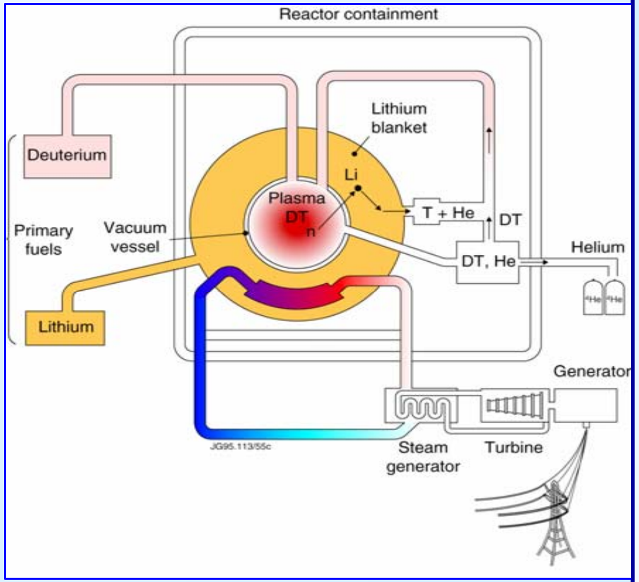
Cross section of present EU D-shape tokamaks compared to the ITER project

Fusion Reactors - Principle

$${}_1D^2 + {}_1T^3 \rightarrow {}_2He^4 + {}_0n^1$$

3.5 MeV heating of plasma

14.1 MeV T production, heat for electricity generation



mass-energy balance

D	+	T	$\rightarrow$	α	+	n
$(2 - 0.000\,994)\times m_p$		$(3 - 0.006\,284)\times m_p$		$(4 - 0.027\,404)\times m_p$		$(1 + 0.001\,378)\times m_p$

$m_p = 1.6726 \times 10^{-27}$ kg

$E = \Delta m \times c^2 = 0.018\,75 \times m_p \times c^2 = 2.818 \times 10^{-12}$ joules = 17.6 MeV

Fusion Reaction: D + T

$_1D^2 + {}_1T^3 \rightarrow {}_2He^4 + {}_0n^1 + 17.6$ MeV

cross-section of fusion reactions

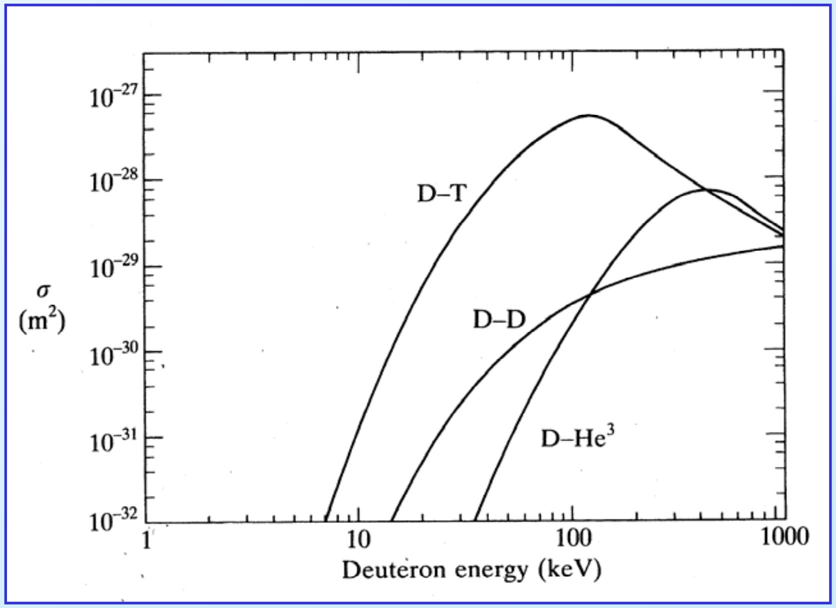
$$D^2 + D^2 \rightarrow \begin{cases} He^3 + n^1 + 3.27 \text{ MeV} \\ T^3 + H^1 + 4.03 \text{ MeV} \end{cases}$$

$D^2 + He^3 \rightarrow He^4 + H^1 + 18.3$ MeV

$\mathscr{R}$ (reaction rate) = $\sigma \times n_i \times v_i \times N$

σ has he dimension of a surface

Hot plasma, $n = n_1 + n_2$, max. for $n_1 = n_2$



Why Fusion Energy ?

- The world will not run out of fossil fuels during the 21st century.
- Fusion is a clean source of energy (no green-house gases, no rad-waste requiring geological repository). CO2.ppt
- Fusion is a safe source of energy (e.g. no evacuation).
- Fusion fuels are available for everybody (energy independence). FusionFuel.ppt
- The above features are essential to achieve social acceptability.
- Moreover, the development of the “hydrogen economy” requires abundant primary sources of energy. Fusion could be one of them.

Socio-Economics → GC. Tosato

PPCS Reactor Models

Towards a Fusion Reactor

ITER -- ? -- FOAK Reactor -- Reactors

"Broader Approach"
- Next Step Machine (e.g. ITER)
- Satellite tokamaks (physics)
- Technology R&D (e.g. IFMIF)

Qualification of components and processes

- High availability
- Safe and environmental-friendly
- Economically acceptable

To demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes

Towards a Fusion Reactor (cont'd)

Considering that:

- European Fusion programme is reactor oriented
- ITER (next step machine) objectives clearly defined

It is necessary to:

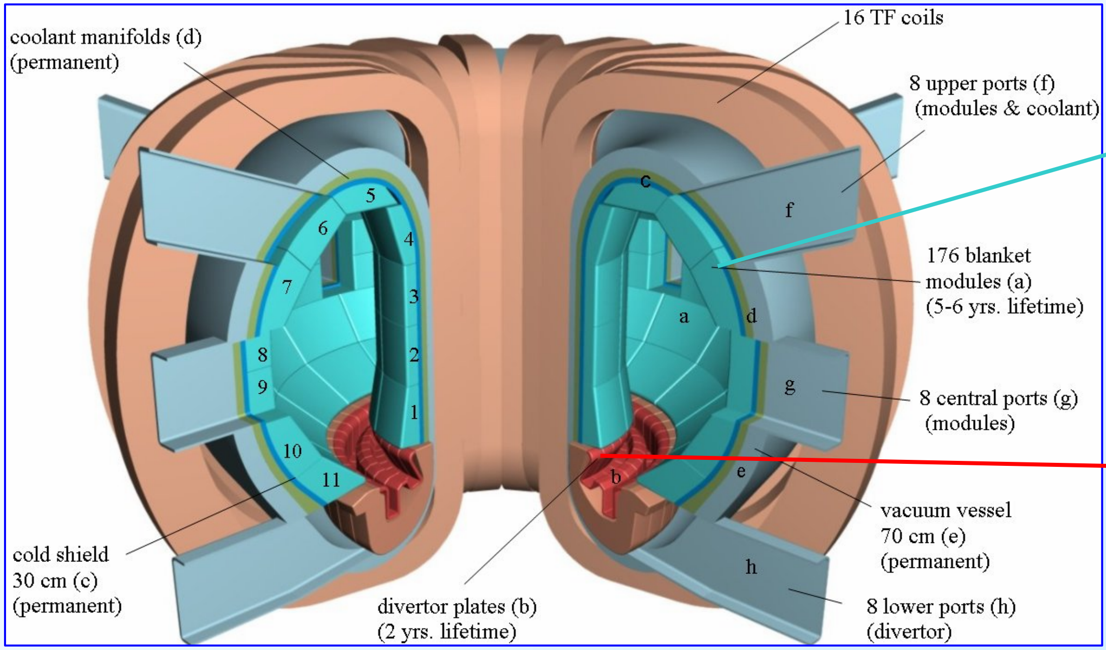
- Confirms that a first commercial fusion power plant will be economically acceptable, with major safety and environmental advantages
- Clarify what devices should be built after ITER (roadmap)

Power Plant Conceptual Study

European PPCS

- to assess the fusion energy status
- to establish coherence and priorities in the EU fusion programme

Tokamak Reactor, layout

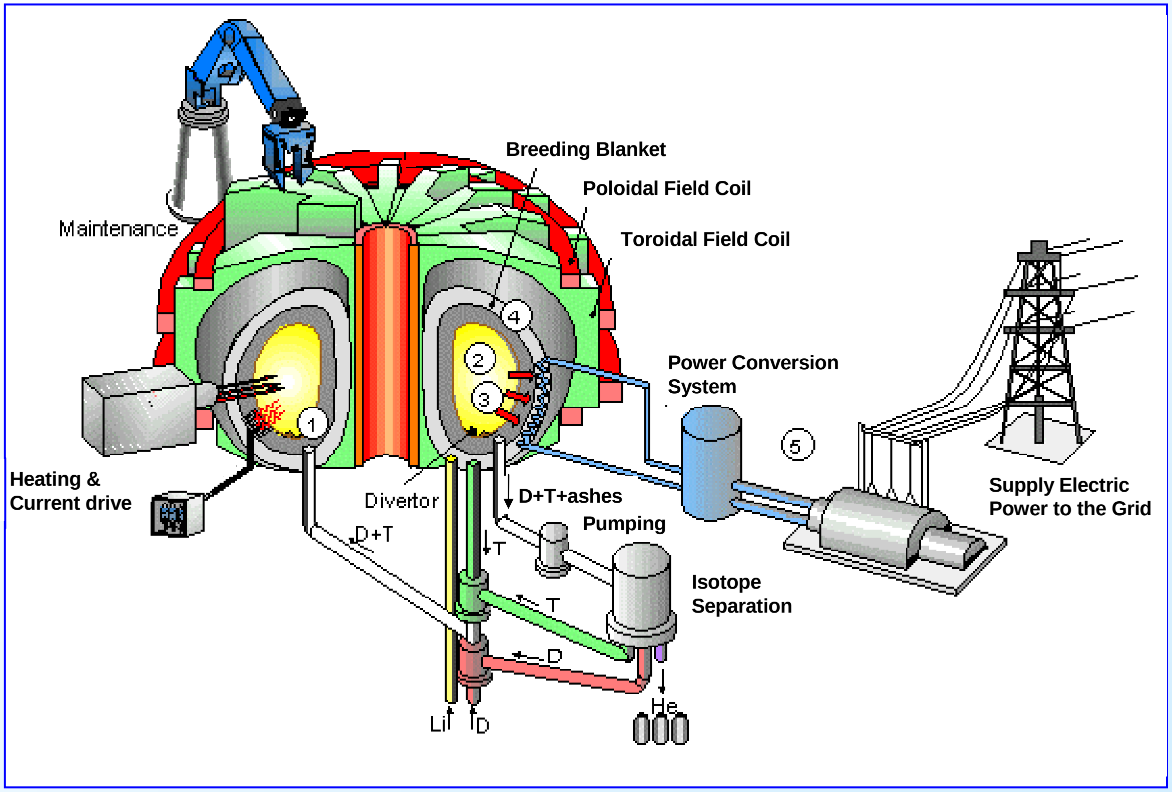


Nuclear Power Core

Blanket
- T production
- Heat recovery
- Nuclear shielding

Divertor
- Ash (He) exhaust, with the associated power
- Heat recovery (desirable)

Tokamak Reactor, layout (cont'd)



Other Main Systems

H & CD

Injection of power into the plasma

Remote Handling

All maintenance inside the bioshield

Magnet system

Balance of Plant

Tritium plant

Main Reactor Requirements*

Safety / Environment

- no need for emergency evacuation, no active systems for safe shut-down, no structure melting following LOCA
- minimum waste transport, minimum waste to repository;

Operation

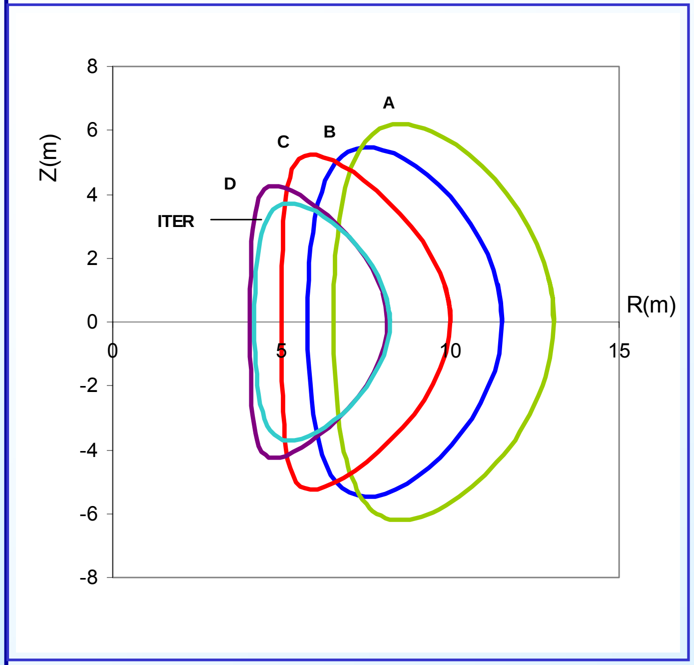
- steady state, ~ 1 GWe, base load;
- availability 75 ÷ 80 %, with only few unplanned shut-downs/year;

Economics

- public acceptance could be even more important than economics
- economic comparison among equally acceptable energy sources
- licensing/regulation requirements strongly reduced vs. fission
- construction time ≤ 5 years

* Recommendations from EU utilities/industry

PPCS Models



4 plant models developed, ranging from “limited” to “very advanced” extrapolations in physics and technology, as examples of a spectrum of possibilities (e.g. 3 different coolants considered: water, helium and lithium-lead).

Models selected considering EU blanket concepts development program (DEMO and long term).

Systems code (PROCESS), subject to assigned plasma physics and technology rules and limits, determined the economic optimum for each model.

Compared to earlier European studies, the plasma physics basis is updated and the designs aim to satisfy economic objectives

Plasma physics basis

- Based on assessments made by expert panel appointed by European fusion programme.
- Near term Models (A & B): modest improvement w.r.t. the design basis of ITER - monotonic q profile with q_{95}=3, within the following limits: H_H<1.2, n/n_{GR}<1.2, β_N<3.5 and first stability region.
- More advanced Models(C & D): progressive improvements in performance - high β and high confinement, MHD stabilisation (strong shaping), high bootstrap current fraction and divertor protection.

Physics → C. Kessel
System studies → D. Ward

Fusion Reactors PPCS Parameters

Parameter	Model A	Model B	Model C	Model D
Unit Size (GW_e)	**1.5**	**1.3**	**1.4**	**1.5**
Fusion Power (GW)	**5.0**	**3.6**	**3.4**	**2.5**
Net efficiency	**0.31/0.33**	**0.36**	**0.41**	**0.60**
Major Radius (m)	**9.55**	**8.6**	**7.5**	**6.1**
Plasma Current (MA)	**30.5**	**28.0**	**20.1**	**14.1**
Bootstrap Fraction	**0.45**	**0.43**	**0.63**	**0.76**
P_{add} (MW)	**246**	**270**	**112**	**71**
Recirculating power fraction	**0.28**	**0.27**	**0.13**	**0.11**
Divertor Peak load (MW/m^{-2})	**15**	**10**	**10**	**5**
Av. neutron wall load	**2.2**	**2.0**	**2.2**	**2.4**

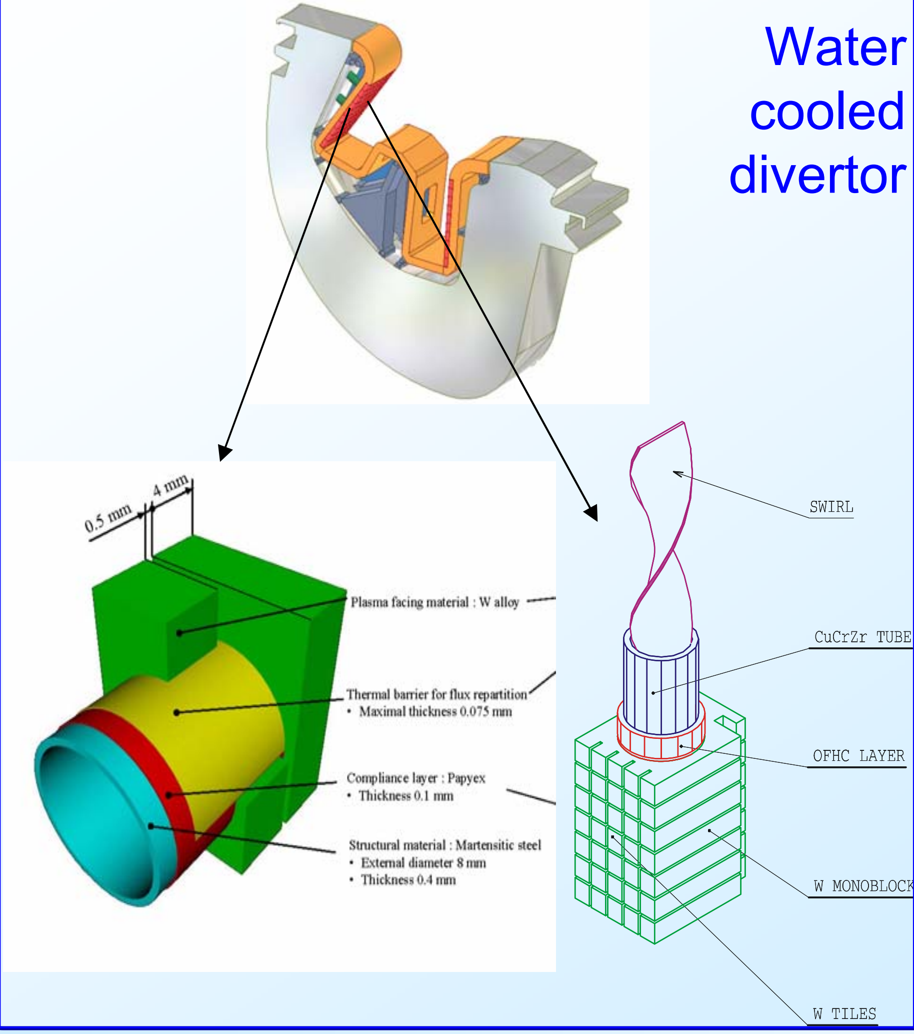
Materials for Nuclear Power Core

Model	Divertor armour	Divertor structure/coolant	Blanket structure	Blanket breeder-multiplier/coolant
A	W alloy	Cu/water or RAFM/water	RAFM	LiPb/water
B	W alloy	W alloy+RAFM/He	RAFM	Li_4SiO_4-Be/He
C	W alloy	W alloy+RAFM/He	RAFM (ODS)	LiPb (SiC)/He
D	W alloy	SiC/LiPb	SiC	LiPb
AB (2004)	same as B and C		HCLL concept	

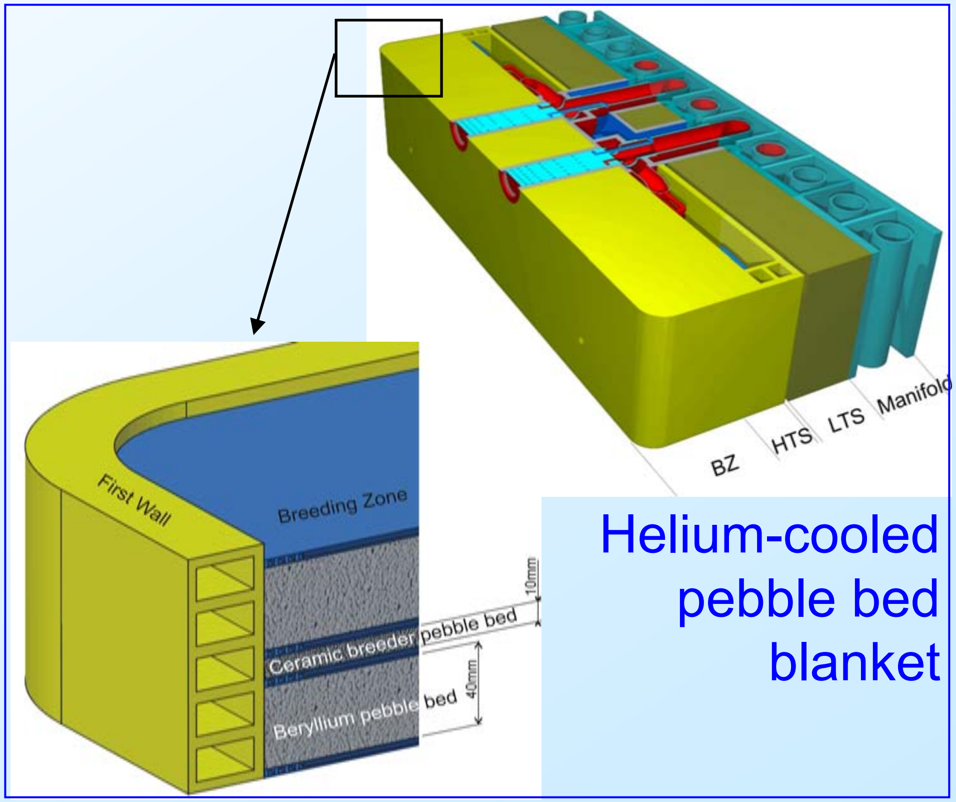
Blanket and Divertors → L. Giancarli
Divertor → G. Janeschitz
Materials → A. Moeslang, B. Van der Schaaf

Typical Internal Components

Water cooled divertor

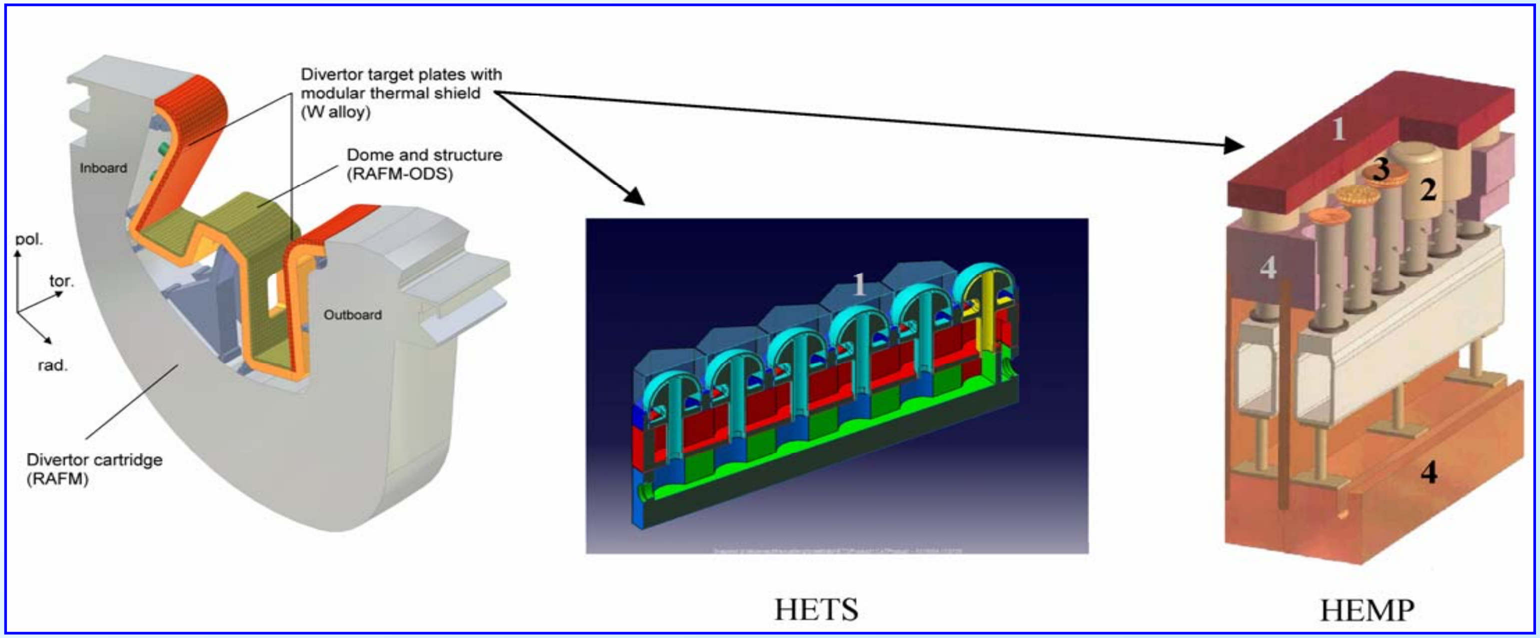


Helium-cooled pebble bed blanket



Key Technical Innovations
helium-cooled divertor concept

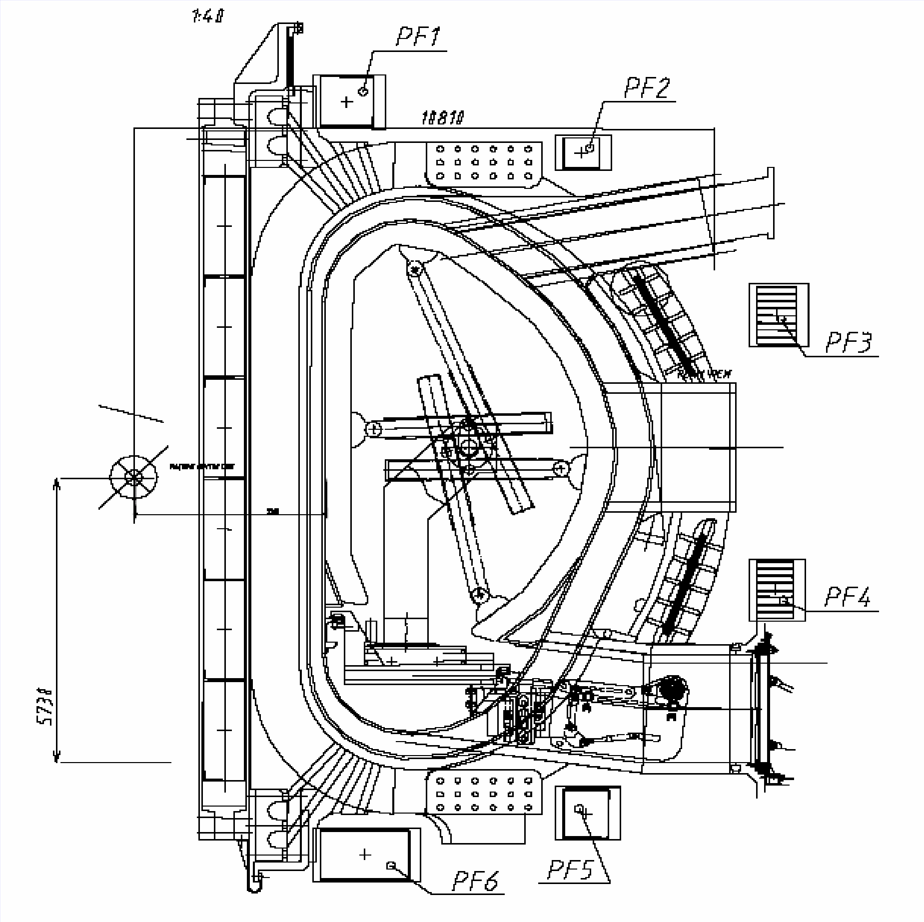
Concept permitting high tolerable heat flux of 10 MW/m²



Key Technical Innovations maintenance

- In-vessel scheduled maintenance driven by # of internal components, by parallel work and by logistics (# shifts, # working hours per shift, transport to hot cell during night shift).
- Replacement time estimates for ITER (1998: 720 BM, 2001: 421 BM) ⇒ # of internal components too high for an availability target of 75%.
- Alternative segmentation in "large sectors" (ARIES) review by PPCS: severe engineering difficulties, availability 75-80%, capital cost due to increased size increase >12.5%. LargeSector.ppt
- PPCS investigated alternative segmentation of blanket in "large modules" without affecting the overall mechanical structure.

Handling of large modules



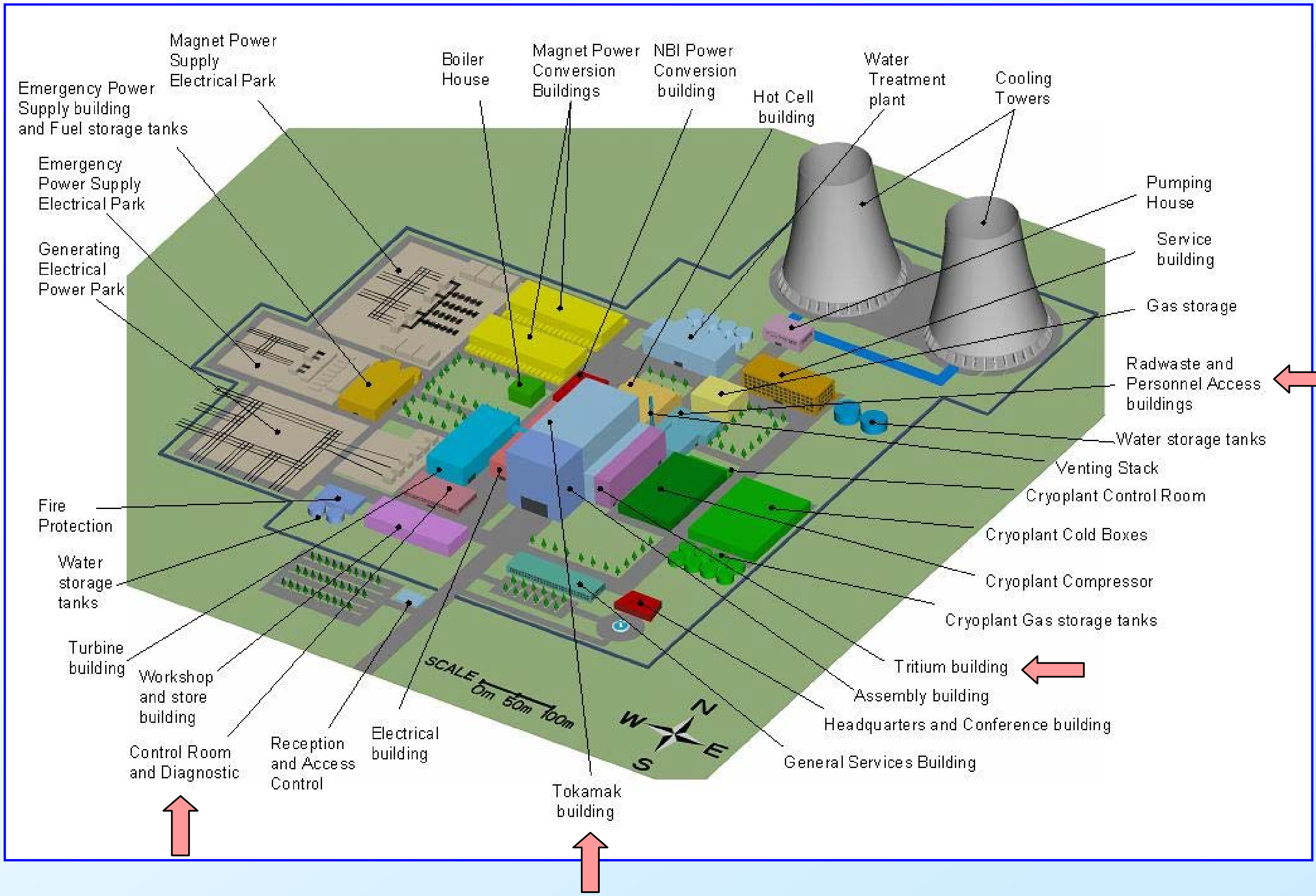
Lifetime: blanket 5 yr., divertor 2 yr.

Estimates for models A (189 BM, 54 DC) and B (162 BM, 54 DC):

- availability between 78 and 85 % (3 and 4 ports, BM and DC handled in series or in parallel)
- include 4% for ex-vessel maintenance but exclude contingencies – at least 5%

(PPCS: 10th of a kind)

Fusion Reactors Plant Layout



Most of the plant is conventional, not fusion specific!

BoP → E. Bogusch

S&E Key Question

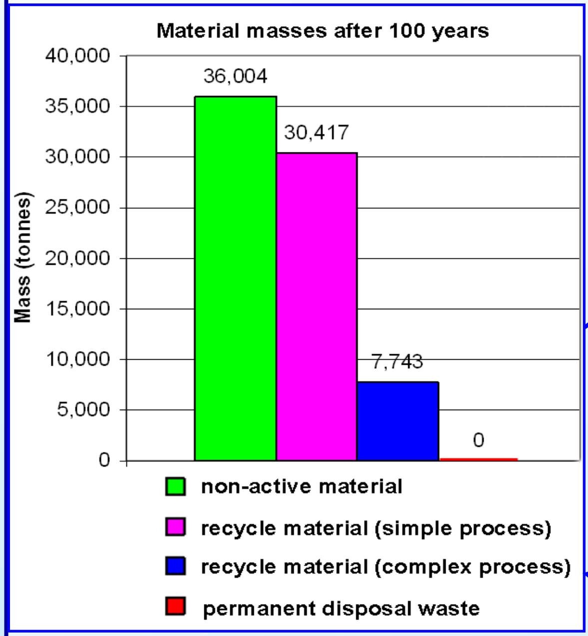
Given that:

- The designs satisfy economic objectives
- The plasma physics basis is new (and so the parameters are substantially different than in earlier European studies)

Do the good safety and environmental features still hold?

Fusion Reactors Safety & Environment

Inherent features: low amount of fuel, reaction stops shortly after fuelling stops, low residual heat, no greenhouse gases, no fissile materials.



Total loss of coolant: no melting, without relying on any active safety system.

Doses to the public after most severe accident driven by in-plant energies (bounding accident): comparable to annual dose due to natural causes, no evacuation.

Accident sequence analysis: much lower doses than for the bounding accident analyses.

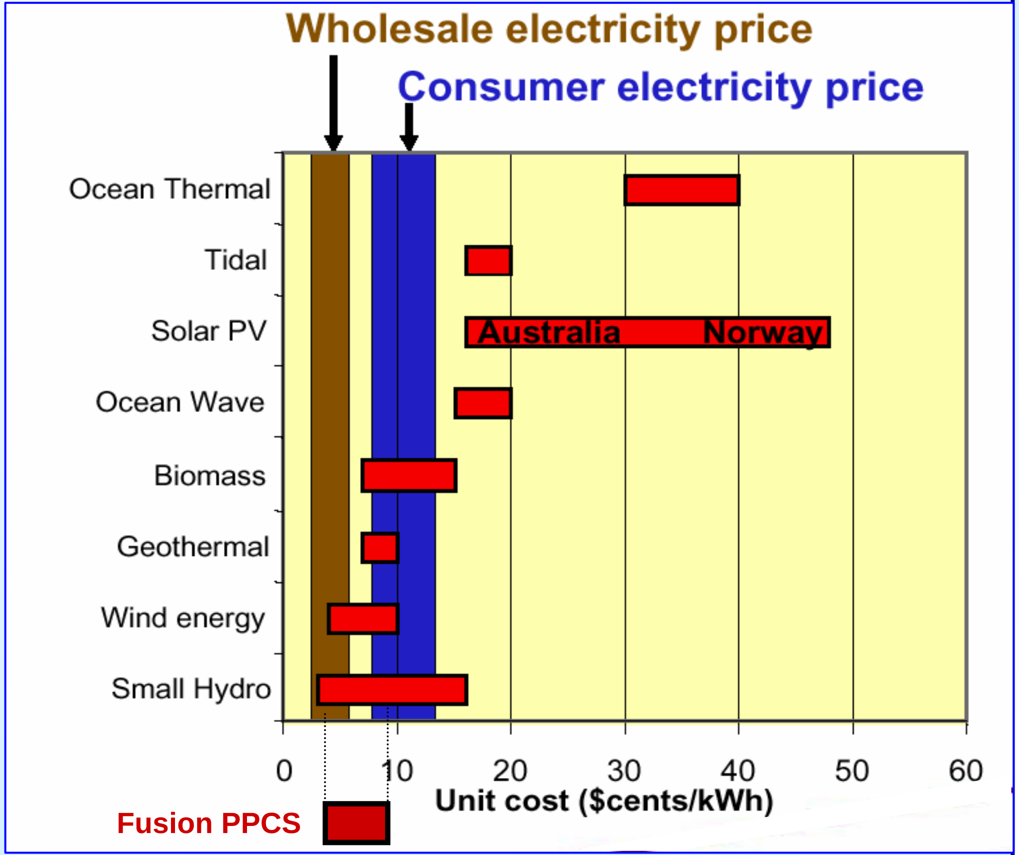
No need of deep geological disposal for rad-waste.

Fusion Reactors
Cost of Electricity

Internal cost of electricity, for the PPCS models, ranges from 3 to 9 Eurocents/kWh

External cost ranges from 0.06 to 0.09 Eurocents/kWh

Even the near-term Models are acceptably competitive



Key Issues

PPCS conclusions

Trade-offs between physics and technology

Technology

PPCS Conclusions (technical)

- Plasma performance only marginally better than the design basis of ITER is sufficient for economic viability (cost of electricity likely to be comparable with that from other environmentally responsible sources of electricity generation)
- Definition of a maintenance concept capable of delivering high availability (75 %)
- Conceptual design of a helium-cooled divertor capable of tolerating a peak heat load of 10 MW/m^2

PPCS Conclusions (S & E)

- The PPCS models confirm the well-attested and attractive safety and environmental features of fusion:
  - loss of cooling events: no melting of structures
  - most severe conceivable accident driven by in-plant energies: no evacuation
  - extremely rare (hypothetical) ultra-energetic ex-plant event: health effects smaller than the typical consequences of the external hazard itself
  - activated material from fusion power stations would not constitute a waste management burden for future generations

PPCS Conclusions (R&D)

- European fusion development programme on the right lines:
  - next step machine (ITER) to demonstrate the scientific feasibility of fusion
  - materials development (low activation martensitic steels and tungsten alloys, more advanced materials)
  - development of “DEMO blanket models”
- More work on:
  - the development of divertor systems (high heat flux tolerance, high temperature operation, adequate lifetime)
  - development and qualification of maintenance procedures (availability requirements of power plants)

Towards a Fusion Reactor

Next Step -- DEMO -- FOAK Reactor -- Reactors

Next Step: scientific and technological feasibility of fusion energy

DEMO: Qualification of components and processes

FOAK Reactor -- Reactors:

- High availability
- Safe and environmental-friendly
- Economically acceptable

Physics vs. Technology

A complete understanding of the physics is the main objective of the next-step (ITER and satellite tokamaks)

Amongst the possible operating scenarios, trade-offs between physics and technology will allow to determine the optimum scenario

Question: if and how to address some of these questions in ITER

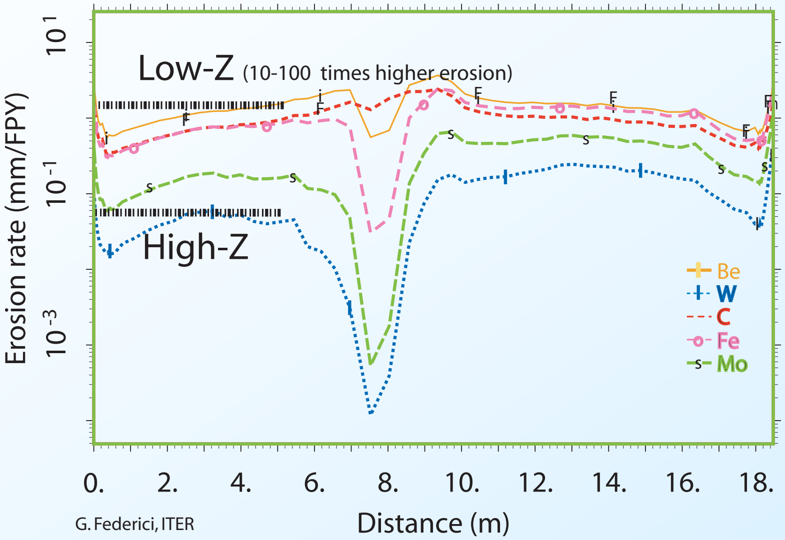
EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT

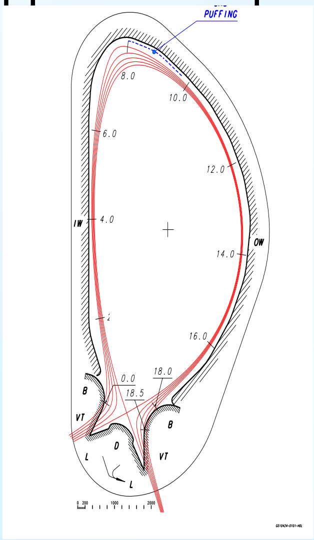
Physics vs. Technology (PWI)

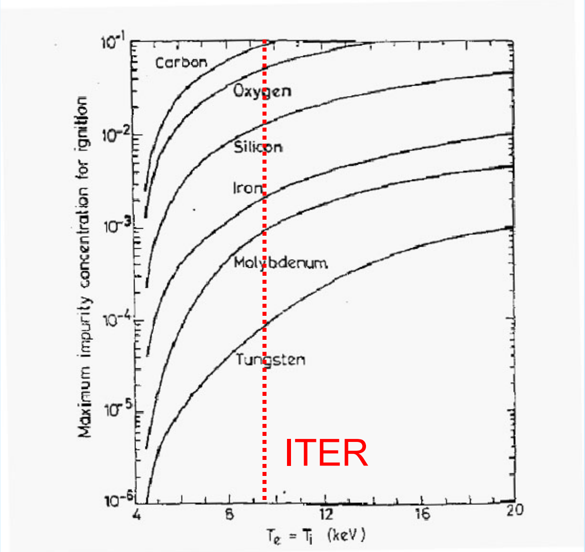
PWI → G. Federici

Impurities → radiative power losses, fuel dilution

Impurities originate from → (1) erosion of plasma facing materials (physical sputtering, evaporation), (2) desorbtion of species trapped in the plasma facing materials, (3) He ashes







DEMO first wall: W ⇒ learn to operate tokamaks with a W first wall. ITER objective ?

ITER: start operations with a W first wall or foresee complete replacement of FW ?

Physics vs. Technology (I_P)

Hypothesis: no disruptions in a reactor, but licensing authorities will require confinement to be guaranteed following the most severe conceivable accident driven by in-plant energies

ASME III class	II (off normal)	III (10^{-4}/yr)	IV (10^{-6}/yr)
Design criteria	S_m	$1.2\times S_m$	$2\times S_m$

EM loads: a major driver for the design of in-vessel components

EM loads scale with dimensions of component, I_P and B

Number of in-vessel components to be minimised to reduce replacement time (major cause of plant unavailability)

ITER: 421 modules, typically 1×1.5 m^2, I_P = 15 MA, B_o = 5.3 T

PPCS: ≈180 “large” modules, 2×4 m^2, I_P = 30 MA, B_o = 7 T (models A and B)

Physics vs. Technology (I_P, cont'd)

Additional power must be minimised ($I_P = I_{BOOT} + I_{CD}$)

- Maximise bootstrap current
- Minimise power for current drive: minimise I_{CD}, maximise efficiency of CD systems ($P_{CD,el} = P_{CD}/\eta_{CD}$)
  (models A and B: η_{CD}=60%, models A and B: η_{CD}=70%)

$\Rightarrow$ Minimise I_P

But $\tau_E \sim I_P \times R^2$, $n \sim I_P$

Remember ultimate goal: produce electricity,
i.e. Q > 10 and acceptable recirculating power fraction

ITER: develop reactor relevant scenarios

Physicists and Engineers: talk to each other!

Technology

Items to be qualified prior to to building DEMO / FOAK reactor:

- Materials
- Systems and components (concept and design) for high availability

Technology (materials)

EUROFER (150 dpa, 550ºC) → Structural material
W alloy → Armour material

→ **model A**

Not good enough for a He-cooled reactor ($T_{He,out}$ > 650 ºC)
EUROFER ODS → Structural material
W alloy → Structural (> 850 ºC) and Armour materials

→ **model B**

- Reliability ⇒ Simplicity ⇒ (Ideally) one coolant only
- Safety ⇒ do not mix water cooling and Be in the reactor
- He-cooled device requires a He-cooled divertor → major challenge
- BoP for He-cooled device not available → large industrial development
  → (initially) low reliability

How credible is a He-cooled DEMO concept ?

Technology (reliability)

H&CD systems → high efficiency (>60%) and high reliability

Reliability ⇒ Simplicity ⇒ high temperature superconductors for magnets (power densities severely limits the interest of B higher than in PPCS)

Reliability ⇒ use qualified components and systems
⇒ all FOAK reactor components and systems to be qualified in DEMO

- Qualify in-vessel maintenance procedures → target for scheduled operations, incl. contingency: > 80% availability
- Ex-vessel maintenance in parallel with scheduled in-vessel maintenance
- Target for unscheduled maintenance: < 5%

Continue investigations on in-vessel maintenance procedures
Think seriously about ex-vessel maintenance (also in ITER)

Conclusions

PPCS Fusion Reactors (summary)

- Why fusion?

  A potentially safe and clean source of energy

- PPCS models (examples of a spectrum of possibilities)

  Confirm S&E attractiveness of fusion

- Issues
  - Physics vs. technology: PWI, I_P
  - Technology: materials (EUROFER, W alloys), coolant for DEMO, availability (maintenance procedures, simple and proven concepts for components)

PPCS Fusion Reactors (future)

Was PPCS successful ?

- It confirmed the S&E attractiveness of fusion
- The analysis are robust: conclusions true for all models, clearly insensitive to limited variations of key parameters
- Study completed, no “further studies”

YES, the PPCS was successful

Follow-up

- DEMO study, to address most of the issues presented in the correct “time-frame” (i.e. after ITER, before FOAK reactor)