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ENEA

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

DEMO design and Diagnostics : a short summary of studies in EU

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Outline

1. Short Introduction on present status of tokamak plasma scenarios

2. DEMO design principles(tokamak fusion energy demonstrator) :
- MODELS for DEMO steady state and pulsed devices,
- physics analysis
- pros and cons

3.DEMO diagnostics and controls :
- principles of fusion reactor control and sensors (diagnostics)
- Minimum set of diagnostics for DEMO (pulsed and steady state)
- Necessary diagnostics for machine protection and burn control
- R&D needed

4.Conclusions

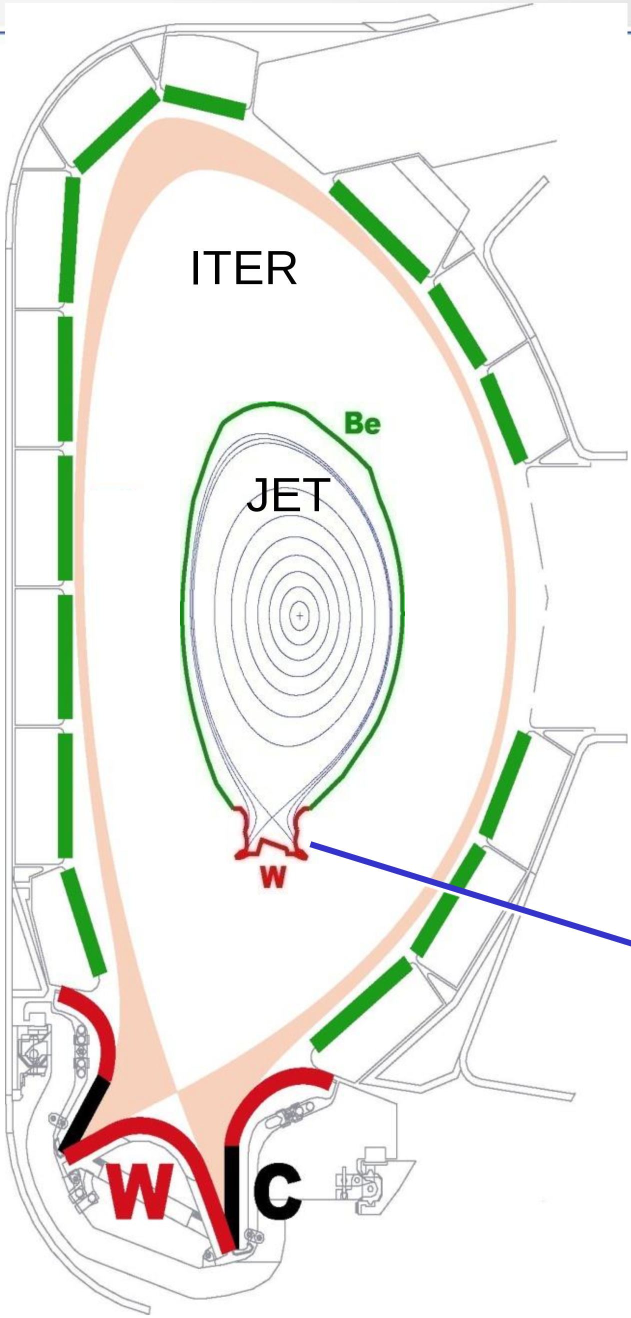
Aims :
Where we are in the plasma scenarios

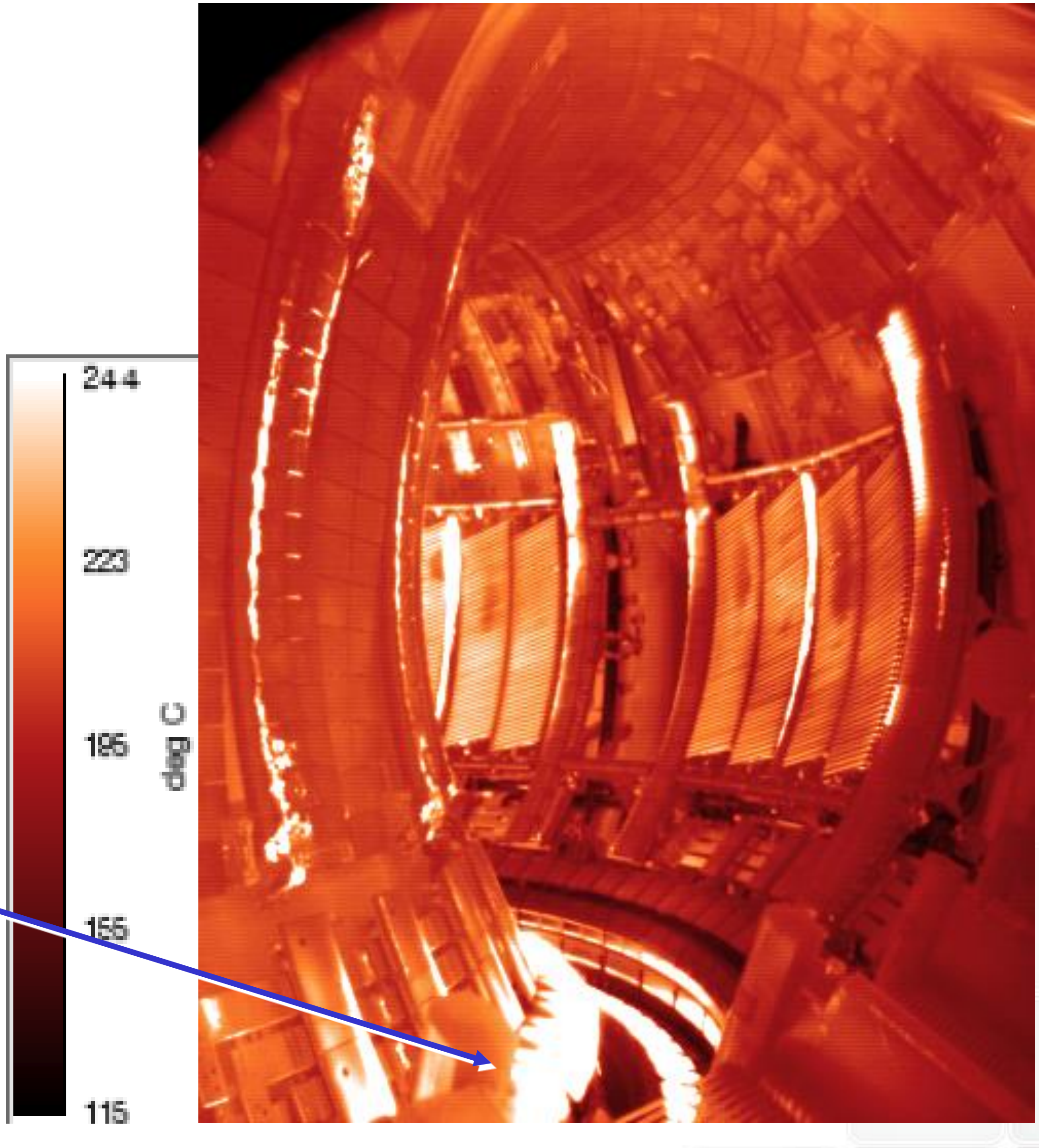
EU FUSION ENERGY ROAD MAP

Key points on the design
Of DEMO, motivations for a
Pulsed DEMO

The diagnostics are sensors
For DEMO controls
NO PHYSICS STUDIES ON DEMO
Few systems only for
BURN CONTROL and
Machine protection
KEY POINT : The resistence to
neutron fluence
(total neutron flux integrated in time)

JET and ITER

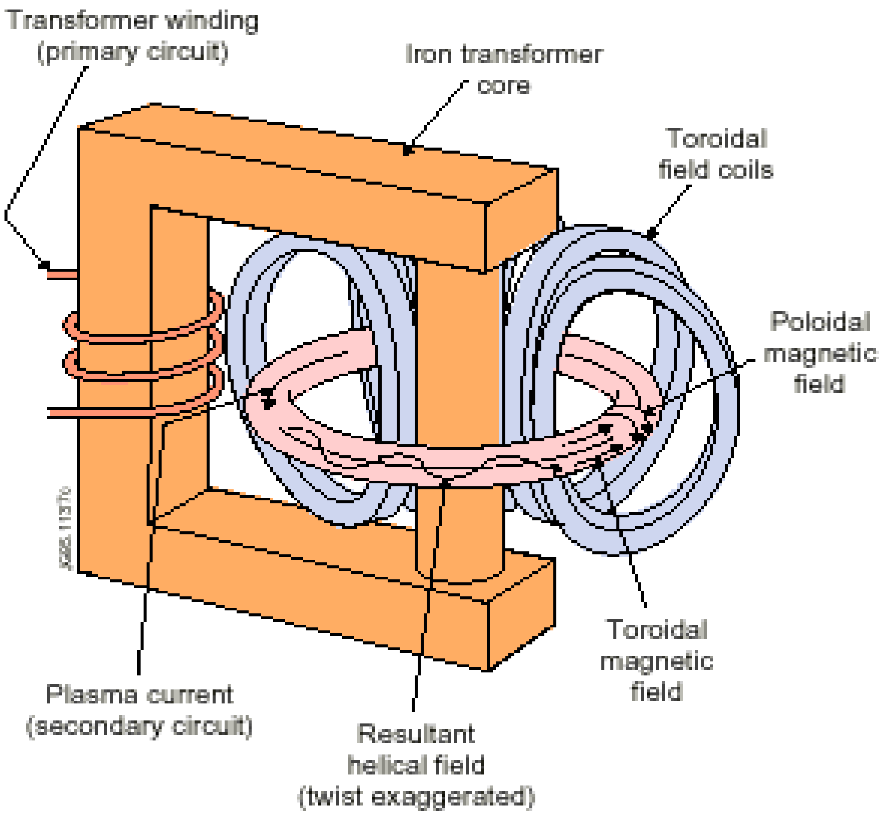




JET discharge as seen by a IR camera

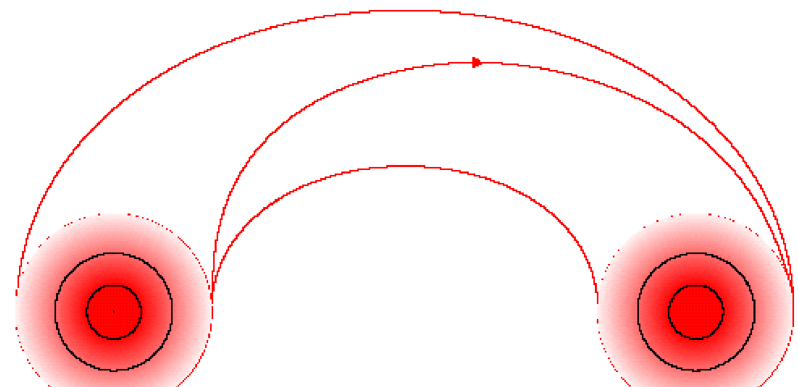
F P Orsitto ENEA Frascati

Scheme of a tokamak



In a plasma contaned in a toroidal device with axial magnetic field a current is induced by a transformer

A magnetic field results with elical field lines which close after a certain number of turns on surfaces called 'rationale surfaces'



Bpol~ Btoroidal/10;

Safety factor   q=(number of toroidal turns /n poloidal turns)

$$q = \frac{5a^2 B}{RI}(1 + k^2/2)$$

magnetic shear S= (q/r) (dq/dr)

Physics of confinement

Regimes of plasma confinement are classified in relation to the spatial scales relevant :

i) Regimes where the relevant spatial scale is the plasma dimension are named L-mode (low confinement modes)

ii) Regimes where the Larmor radius is the fundamental relevant scale are named H-modes (High Confinement)

the transition to H-mode is linked to a threshold power $P_{L\text{-}H} \sim C\ B_T\ n^{0.75}\ R^2$.

For example in JET $P_{L\text{-}H}$ ~8MW

confinement scaling laws

Kadomtsev(1975) e Connor e Taylor(1977) demostrated

$$\omega_c \tau_E \propto B\tau_E \propto f(\rho^*, \beta, \nu^*, q,..)$$

fit of data of confinament multi machine database

$$\omega_{ce}\tau_E \propto \rho^{*-2.7} \beta^{-0.9} \nu^{*-0.01} \, (scaling \;\; IPB98(y,2))$$

Recent Experiments on JET(EU) e DIIID(Ga, USA) dimonstrated that in the range of parameters useful for a demonstrative reactor

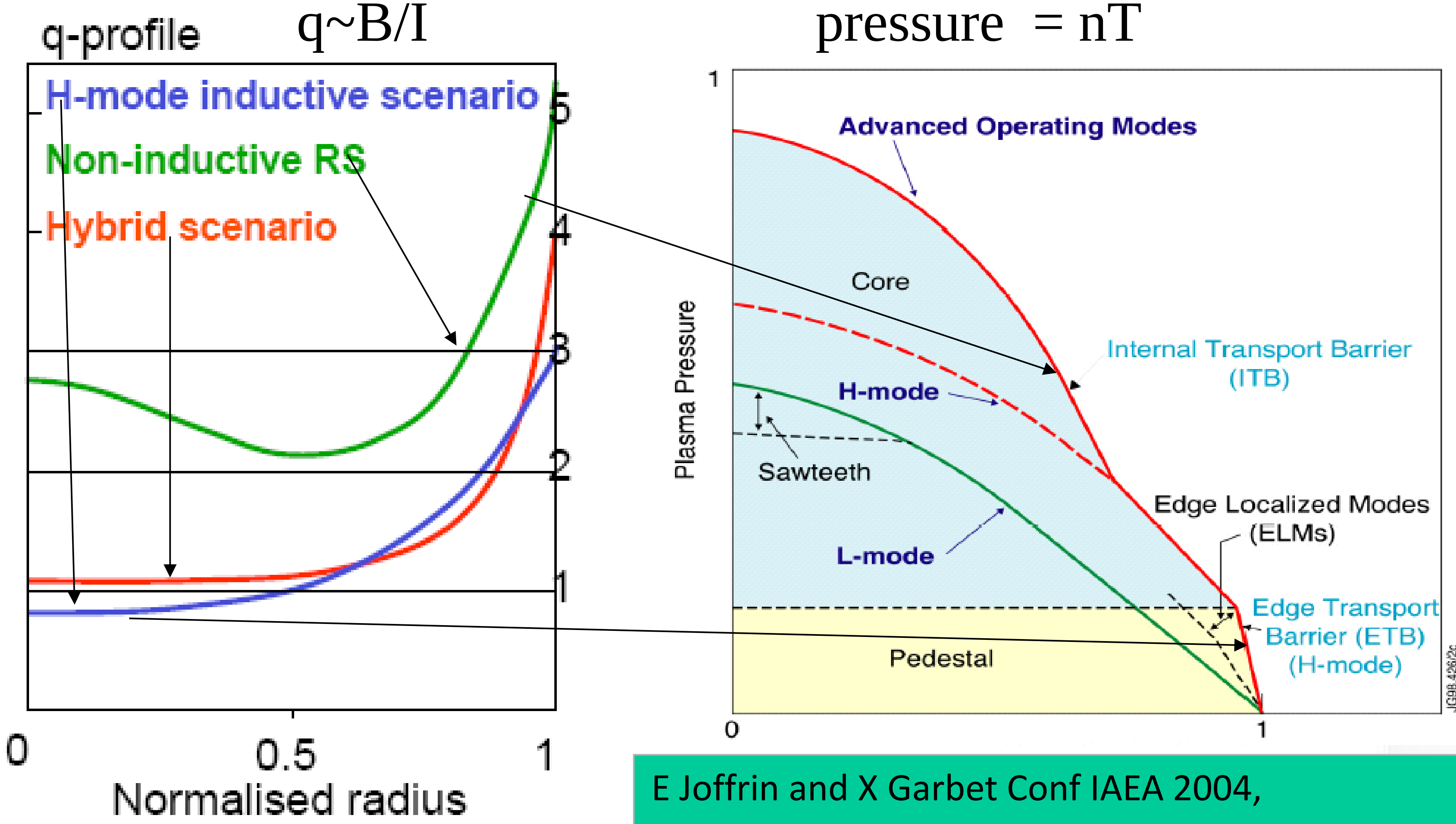
$$\omega_{ce}\tau_E \propto \rho^{*-3.0\pm0.3} \; \beta^{0.0} \nu^{*-0.3}$$

(D McDonalds and J Cordey Conf IAEA 2004,

McDonalds IAEA 2006, Valovic Nuclear Fusion 2006)

operational regimes in a tokamak: correspondence of current profiles ↔ pressure profiles

q~B/I pressure = nT



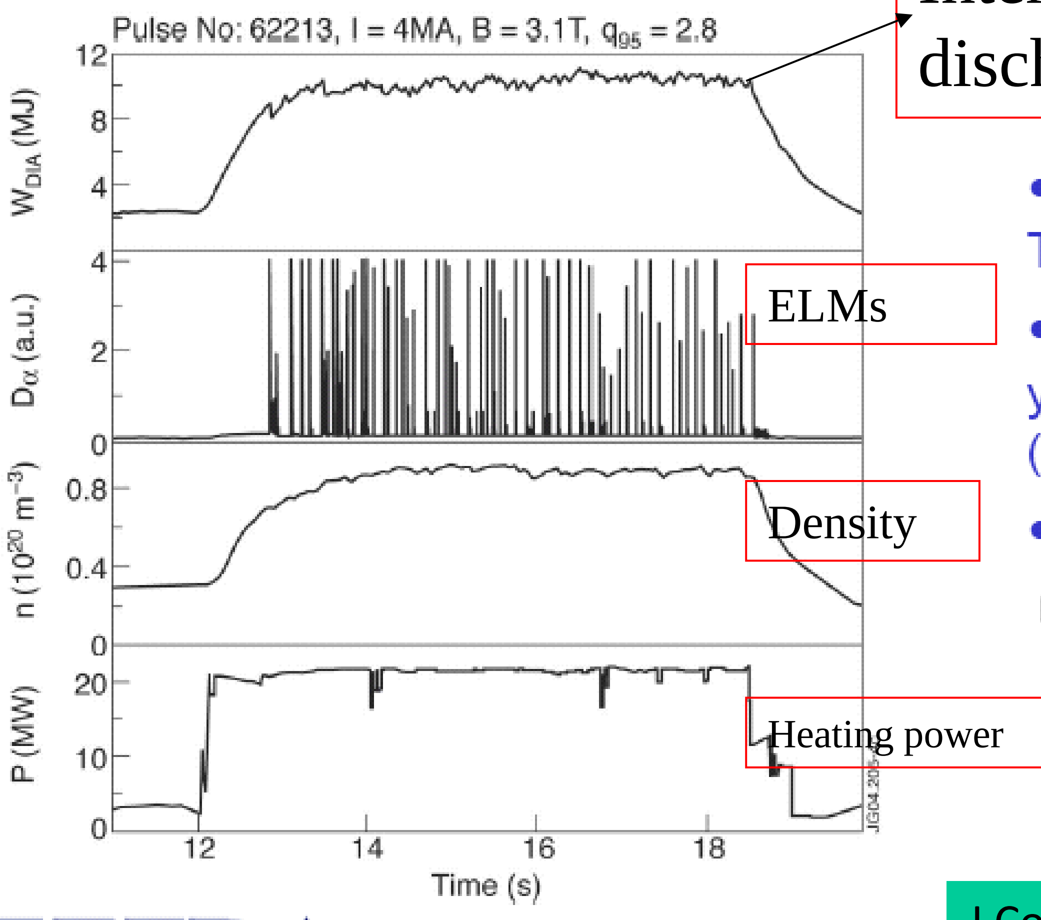
E Joffrin and X Garbet Conf IAEA 2004,

T Luce IAEA FEC Conference 2006

Example of a discharge in ELMy H-mode

ELMs (edge localized modes) corrispond to instabilities generated when locally the beta limit is reached

Internal Energy of the discharge

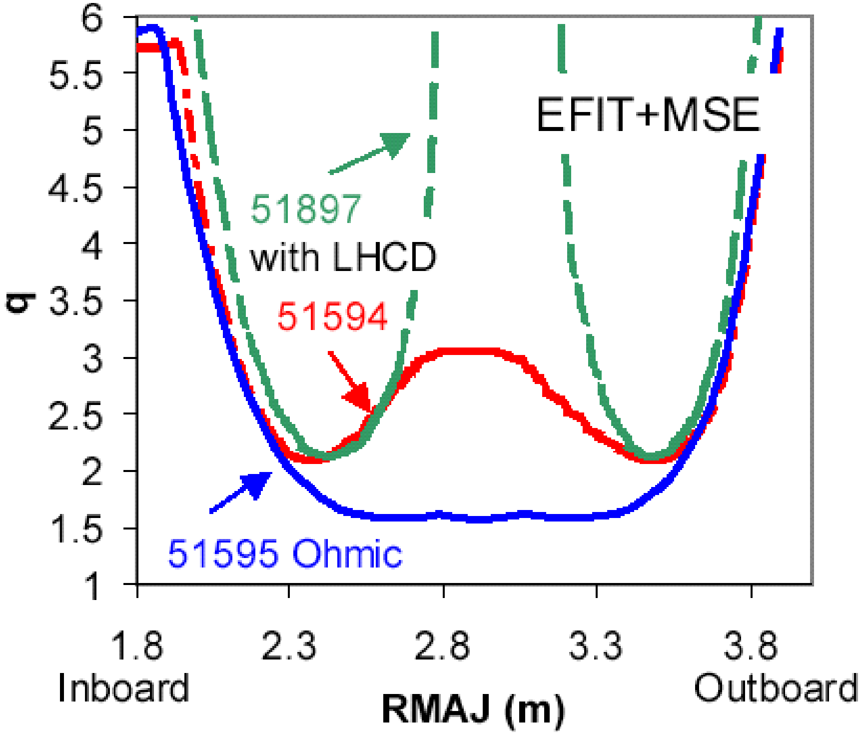


- Max. I_p=4MA, β_N=1.5, Type I ELMy H-Mode
- One of the highest D-D yields achieved on JET (Dec2003)
- ρ^* close to ITER $\rho^*/\rho^*_{ITER} = 1.7$

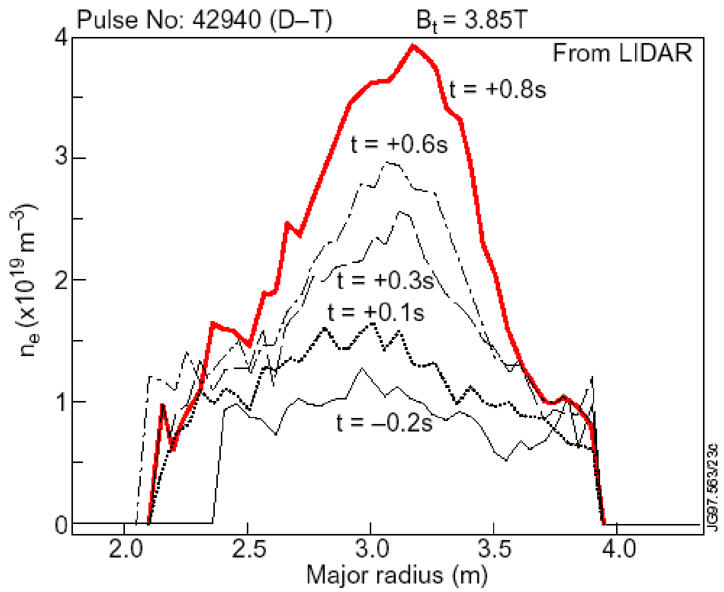
J Cordey et al. Conf. IAEA 2004

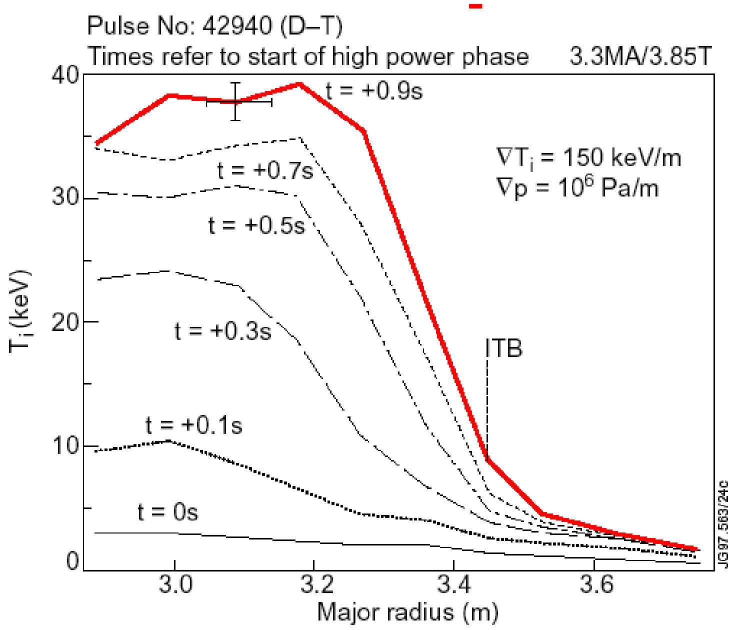
Advanced Scenarios :current profiles and formation of internal transport barriers

- **Improved LHCD coupling leads to strong magnetic shear reversal during preheat**
- **strong internal transport barriers**
- **virtually no power threshold when compared to Optimised Shear**



Internal Transport Barriers in Advanced Tokamak discharges





Profiles of density and ion temperature in JET record discharge in the FIRST Deuterium Tritium campaigns.

Power from fusion in magnetic confinement

P_{fusion}=1/4 n_{ion}^2 <σ v> E_{fusion} ~ $(nT)^2$

P_{fusion} = 1.08 β^2 B^4. MW/m^3.

β=2 nT / ($B^2/2\mu_0$) = [kinetic total pressure(ions+elettrons)] / magnetic pressure

For example. ($B^2/2\mu_0$) = 10000 pascal @ B=0.5T

Typical value of beta β~1-10%

Comments on Pfus vs (limits of) beta

$P_{fusion} = 1.08\ \beta^2\ B^4.\ MW/m^3.$

$D+T \rightarrow \alpha(3.5MeV) + n(14.1MeV)$

$$Q_{\ fusion\ gain} = \frac{fusion\ power}{heating\ power}$$

$$at\ the\ steady\ state \Rightarrow P_{heat} + P_{alpha} = \frac{3nT_e}{\tau_E}$$

$$\tau_E = energy\ confinement\ time$$

$$Q = \frac{Pfus}{\frac{3nT_e}{\tau_E} - \frac{Pfus}{5}} = \frac{\overline{Q}}{1-(\overline{Q}/5)}$$

$$\overline{Q} = \frac{Pfus}{Ploss} = \frac{4\beta^2 B^4 \tau_E}{3}$$

β limited by MHD stability

$$\overline{Q} = \frac{P_{fus}}{P_{loss}} = \frac{4\beta^2 B^4 \tau_E}{3}$$

τE limited by the turbulent transport

Gain Q versus geometry and plasma parameters

Scaling of confinement time

$$\tau_E(s) = 0.0562 * I^{0.93} * B^{0.15} * \left(\frac{a}{R}\right)^{0.58} * R^{1.97} * n^{0.41} * P^{-0.69} * M^{0.19} * k_a^{0.78}$$

$$\beta = \beta_N \frac{I}{aB}; \quad \beta_N \le 0.035$$

Beta limit

$$\overline{Q} = \frac{4}{3}\beta B^2 \tau_E = \frac{4}{3} * 0.0562 * \beta_N * I^{1.93} B^{1.15} * \left(\frac{R}{a}\right)^{1.39} * a^{0.97} * n^{0.41} * P^{-0.69} * M^{0.19} * k_a^{0.78}$$

$$nGR = \frac{I}{\pi a^2}$$

Density limit

$$\overline{Q} \le 0.04686 * \beta_N * I^{2.34} * B^{1.15} * \left[\frac{R}{a}\right]^{1.39} * a^{-1.03} * P_{loss}^{-0.69} * M^{0.19} * k_a^{0.78}$$

The gain factor depends upon :

- **Geometry (a(minor radius) and aspect ratio R/a)**
- **Plasma current I,**
- **magnetic field B**
- **beta β_N.**

At a fixed geometry(R/a), magnetic field B and heating power P an increase of β_N and I of 10% → **33%.** increase of Q

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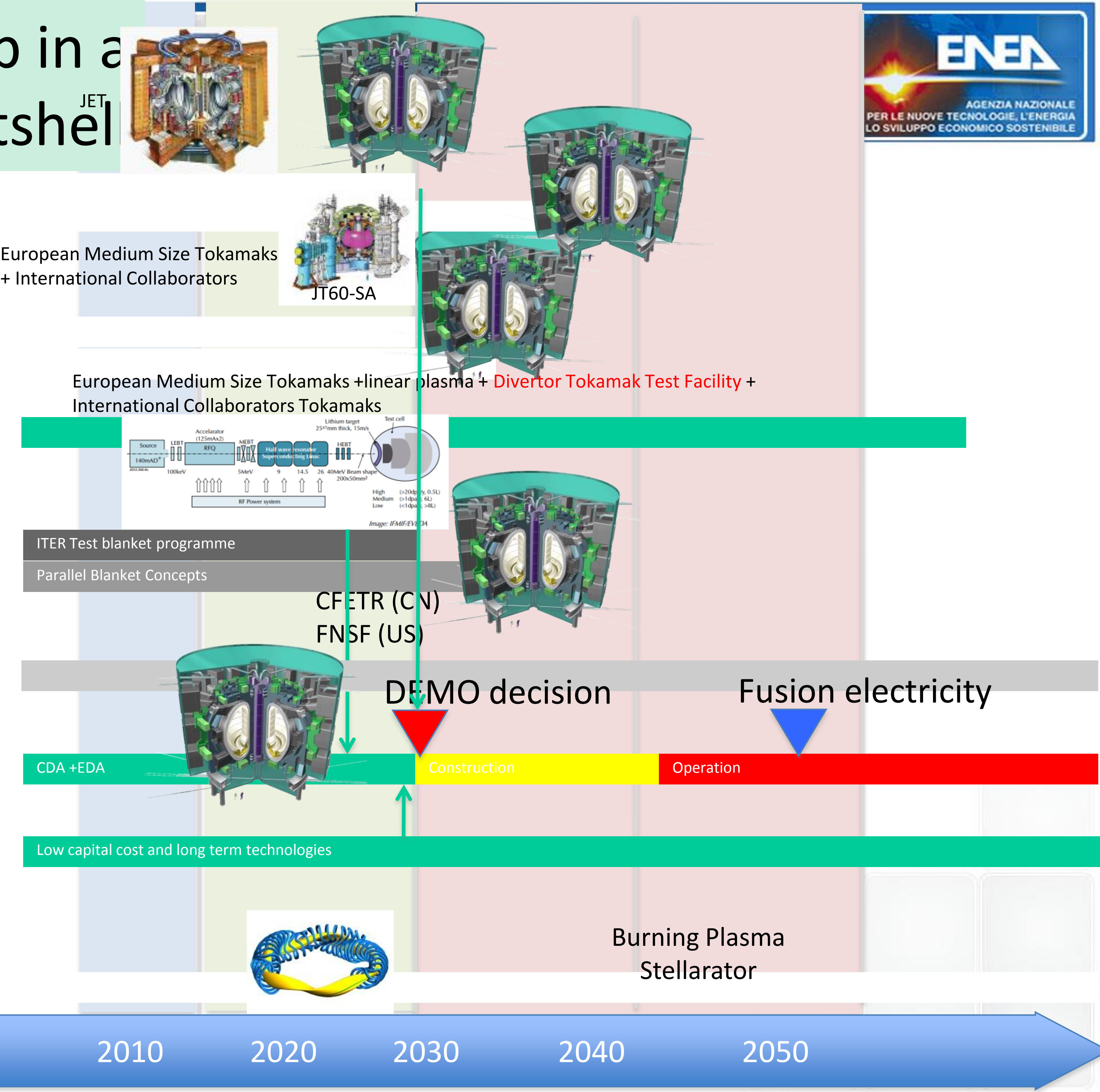
DEMO DESIGN :
STEADY STATE AND PULSED MODELS

EU Roadmap in a nutshell

1. Plasma operation
2. Heat exhaust
3. Materials
4. Tritium breeding
5. Safety
6. DEMO
7. Low cost
8. Stellarator



Basic idea of steady state reactor

The idea of working at high β_N allows for a device with lower current and dimensions since Pfus~$(\beta_N)^2 * Ip^2.*Bt^2.R*k$

Minimizes the heating and current drive needs , since it allows higher values of beta poloidal and self-generated plasma current (bootstrap current) .
In fact the fraction of bootstrap current scales as
(A=R/a=aspect ratio, βp=beta poloidal, Ib=bootstrap current, Ip=total plasma current :

$$f_B = \frac{I_b}{Ip} \approx \frac{1}{3} A^{-1/2} \beta_p$$

$$\beta_p \propto \beta_N / \beta_T$$

$$\beta_p = c q_{95} A \beta_N$$

→ High βp, low A
And high βN

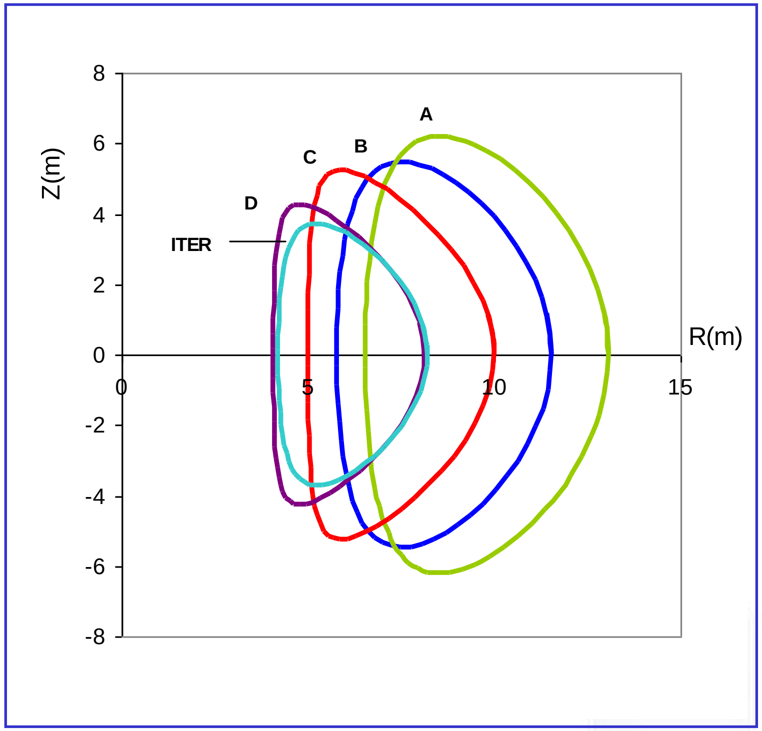
The remaining part of the current must be supplied by Current Drive systems

The produced electric energy must be partly used for the Current Drive system: this part is A critical requirement for a SS reactor.

Analysis of SS DEMO MODELS

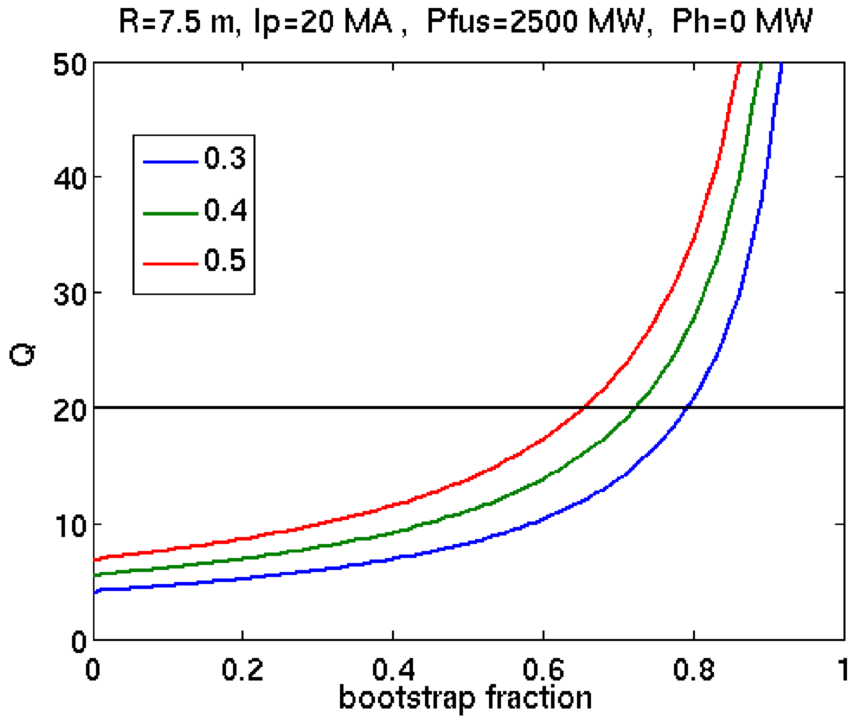
EXAMPLES OF SS MODELS

	ARIES RS	PPCS C	SLIM CS	ITER SS
R(m)	5,5	7,5	5,5	6,2
a(m)	1,375	2,5	2,1	2
Aspect ratio R/a	4	3	2,6	3,1
B(T) on axis	8	6	6	5,3
I(MA)	11,3	20	16,7	9
βN	4,8	4	4,3	2,9
fB	0,88	0,63	0,75	0,46
n/nG	1	1,5	1	0,78
HH(IPBy2)	1,15	1,3	1,3	1,6
Q	27	30	29,5	5
k elongation	1,9	1,9	2	1,8
δ triangularity	0,5	0,47	0,35	0,4
Fusion Power(GW)	2,17	3,41	2,95	0,36
Heating Power(MW)	80	112	100	70



EU PPCS Models

Analysis of DEMO scenarios (PPCS C, SS)



for realistic Current Drive values ($\gamma CD \approx 0.3\text{-}0.4\ 10^{20}$ A W^{-1} 10^{20} m^{-2}) high bootstrap fraction is required $fB \geq 0.7\text{-}0.8$ compatible with the power available of 110MW.

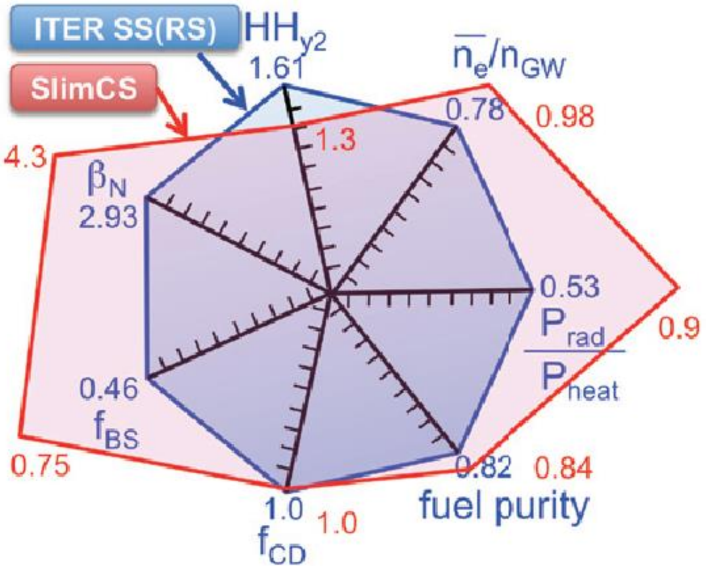
In the PPCS papers a more optimistic $\gamma CD \approx 0.7\ 10^{20}$ A W^{-1} 10^{20} m^{-2}, is assumed

γ_{CD} (A W^{-1} 10^{20} m^{-2})

Analysis of DEMO scenarios (J Garcia et al 2008)

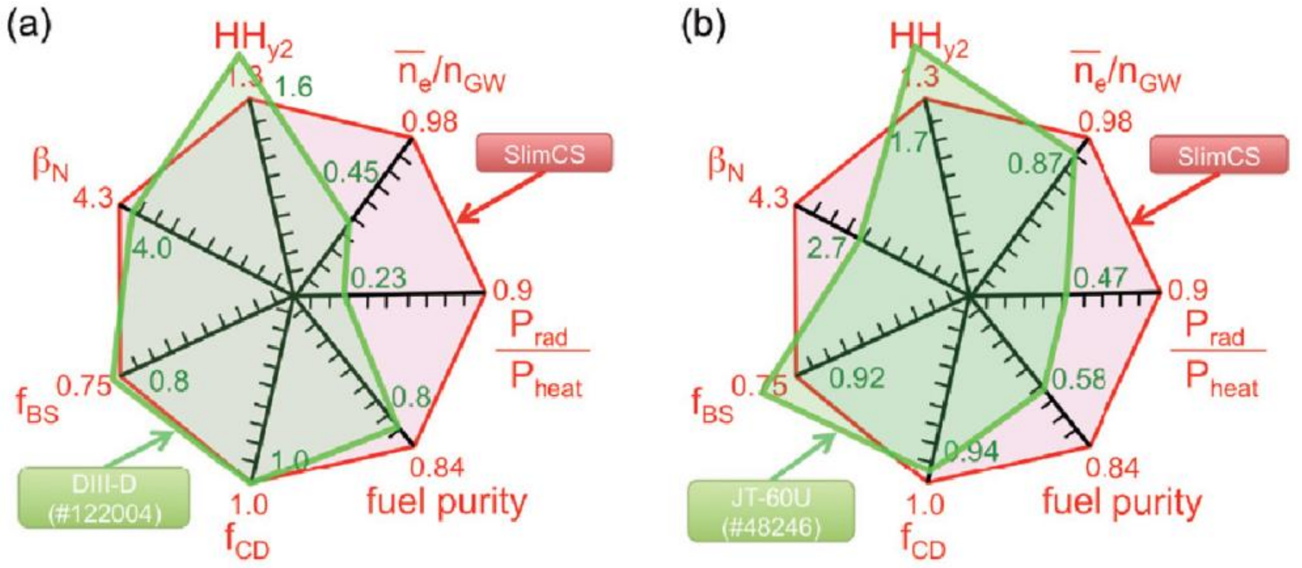
Physics critical issues of SS DEMO

ITER steady state scenario assumes parameters
(HHIPBy2=1.61, βN=2.93,fB=0.46, n/nG=0,78) never demonstrated in integrated way in present devices.
Clearly for SLIM CS the same notation can be applied even more.



Y Sakamoto et al 2010

Achieved performances on DIIID and JT-60U in transient conditions



Integrated performances achieved in transient conditions .
Comparison Of design values of SlimCS (red contour)
and a) DIII-D discharge (#122004) and b) JT-60U discharge (#48246)

DIIID /JT-60U discharges details

The DIII-D discharge shows an impressive set of parameters :
β_N≈4, HHy2≈1.6, fB=0.75 , at a qmin≈2 and q95=5,
produced in a reversed shear q-profile,
in presence of Internal Transport Barrier(ITB).
Multiple feedback controls are needed to reach these achievements including resistive wall mode control using internal and external sets of magnetic coils ,
beta control using neutral beam injection
and electron density control using gas-puffing.
This dischange was run at low density and low radiation fraction.

The JT-60U discharge shown in fig.exhibits values
HHy2=1.7, fB=0.92, ne/nG=0.87 , b_N≈2.7
realized in a reversed shear q-profile with formation of ITB .
Although this discharge has achieved HHy2, fB and ne/nG reactor relevant the remaining issues are β_N, fuel purity, and radiation fraction.

Pulsed DEMO design criteria

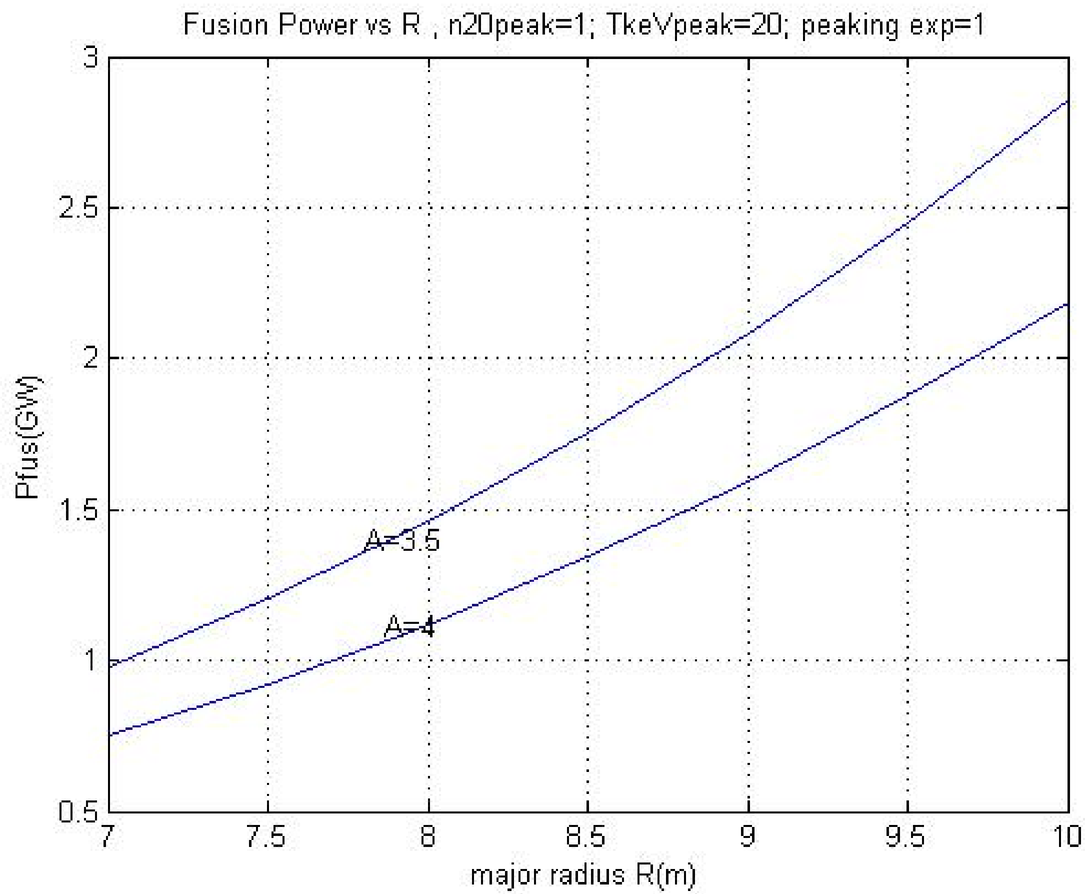
DEMO design

By specifying the aspect ratio, magnetic field, fusion power, temperature, density and fraction of Greenwald density, the size of the device and its plasma current is determined (the plasma current determined from n and Greenwald fraction, not from confinement requirements).

The H-factor is derived from power balance considerations rather than providing it as an input. In that way, a self-consistent solution to the simplified problem can be found.

Pulsed DEMO: model parameter design

A pulsed ractor O3GW
A=3.5 for 2.5GW R=9.5m
A=4 for 1.6GW R=9m
Npeak=1 $10^{20} m^{-3}$



The pressure profile is given by

$$nT = \hat{n}\hat{T}\left(1-\left(\frac{r}{a}\right)^2\right)^{\upsilon}$$

$$In\ the\ figure\quad \upsilon = 1$$

$$P_f = \frac{0.15}{2\nu+1}\frac{R^3}{A^2}k\left(\frac{\hat{n}}{10^{20}}\right)^2 \hat{T}_{kev}^{\ 2}\ MW$$

Determination of Ip, Bt

The plasma current is determined from the Greenwald density limit
Line average $nG = Ip/(\pi a^2)$
Since the $neL = 0.67 npeak$:

$$Ip(MA) = \frac{0.67}{0.8} \pi a^2 \frac{\hat{n}}{10^{20}} = 19.37$$

$$B_T = \frac{q95}{5} \frac{A^2}{F_A S} Ip$$

q95=3-3.5, k=1.75,
δ=0.45, A=3.5 ,
Ip=19MA

we obtain:

a B_T=6.5T corresponding to q95=3.5

Relation Padd and H

$$\left(\frac{Wth}{H_{IPBy2}\ f}10^{-6}\right)^{3.23} + (-P_{fus}/5 + (P_B + P_{syn} + P_{line-core}))/10^6 = P_{AddHeat}(MW)$$

$$P\alpha - (P_B + P_{sync} + P_{line}) = \frac{2470}{5} - 363 = 131;$$

$$P_{AddHeat} \approx 5.2^{3.23} * H_{IPBy2}^{-3.23} - 131$$

For the plasma parameters considered
(T0=20keV, n0=1 $10^{20}m^{-3}$, BT=6.5T,Ip=19MA,
fraction of Argon fAr=nAr/ni=0.1% ,
and beryllium fraction fBe=1%),
the evaluation of the power loss appearing is:
P_B≈165MW, P_{sync}≈6MW,
$P_{line-core}$≈PBe+PAr=2.4MW+190MW; Wth=383MJ;f=220;
HIPBy2=1
$P_{AddHeat}$=74MW

Ploss Total = 363MW
Palpha = 494MW

D3GW vs DEMO1 and PPCS A models

	O3GW	DEMO1 [13]	PPCS A[4]
R(m)	9,5	9	9,55
a(m)	2,7	2,25	3,18
A	3,5	4	3
B	6.5	7,1	7
Ip	19	16	30,5
n20 (fG/Greenwald)	1(0.8)	1.2(1.)	2,3(1.2)
PH(MW)	74	50	246
Q	34	17	20
HHIPBy2	1	1	1,2
Pfus (GW)	2,5	1,9	5

The parameters of the O3GW device differ substantially in the ASPECT RATIO and density with respect to DEMO1 device

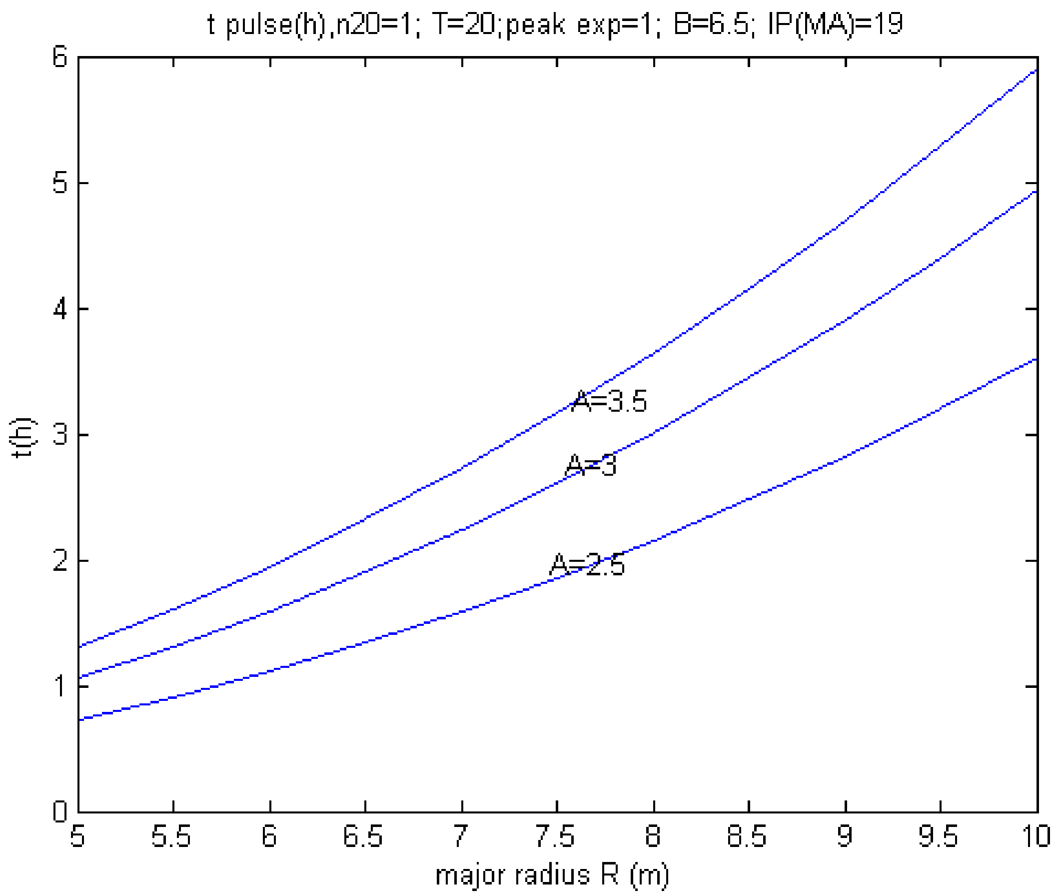
The PPCS A exhibit similar geom parameters to O3GW.
The pulse length of O3GW could be compatible with tpulse= 6h (see ref H Zohm) .

Demo1 CALCULATED
BY PROCESS SYSTEM CODE

PLS pulse length

$$\tau_{pulse} = R^2 \frac{c_3\, q_{95}\, A_r^{\,2}\left(\frac{A_r - 1}{A_r} - \frac{b}{R}\right) - c_4 B}{c_5 B\, A_r^{\,2}(1 - fCD - c_6 * 0.7 q_{95} * \beta_N * \sqrt{A_r}}$$

H Zhom Fus Eng Des 2011



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Steady State vs pulsed

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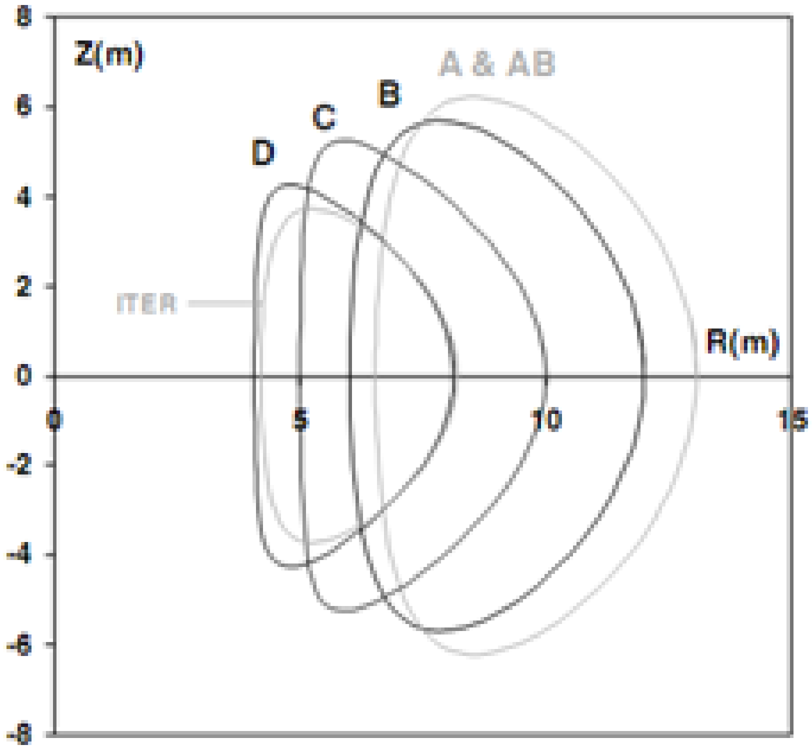
	SS		PULSED
PRO	SMALL R0		RELIABILITY
	SMALL IP		SOLID BASIC PLASMA SCENARIO
	LOW ASPECT RATIO POSSIBLE		HIGH ASPECT RATIO
CONS	LARGE HCD		High COST
	SCENARIO TO BE DEMONSTRATED EXTENSIVELY		CYCLIC FATIGUE ON MAGNETS AND SUPERCONDUCTING COILS
	R&d NEEDED TO MAKE EFFICIENT CD SYSTEMS		PLASMA SCENARIO STILL TO BE COMPLETED
CONTROLS	CONTROLS AND DIAGNOSE OF CURRENT and pressure profiles		TO BE CONTROLLED: divertor and radiation
	MHD CONTROLS: RWM,NTMs		ELM and NTM

Some advantages and issues for pulsed DEMO

The advantages of pulsed DEMO are residing in the fact that we know how to run the H-mode in plasmas where the current is largely inductive. The H-mode is a well established scenario, **however**:

i) there are large uncertainties in the power threshold needed for the access to the H-mode;
ii) the possibility to run plasmas at a density higher than Greenwald density must be validated ;
iii) the tools to mitigate the ELMs must be still fully developed;
iv) The studies of cyclic operations on the machine components inducing creep/fatigue effects on vacuum vessel blanket modules etc are still in the initial phase.



Comparison of Dimensions of PPFC DEMO models with ITER :
Pulsed (A/B) and Steady State C/D

DEMO : DEMO-NSTRATION Device

DEMO SPECIFIC

1.Due to TBR >1 the space available for diagnostics is likely < 5m^2

2.Radiation : $P_{rad}(P_{Br}+P_{Syn}+P_{linecore}) /(P_{alpha} +P_{Heating})$ ~ 75%

3.Wall material /Divertor : metal Tungsten (ITER: Be/W)

4.Neutron fluence : 30-50 X ITER Fluence

5. $P_{alpha}/P_{heating}$:

Device	ITER (Q=10)	DEMO1	DEMO2	ITER SS	SLIM CS	PPCS C
Palpha/Pheating	2	7,16	2,42	1	5,9	6,1
Palpha(MW)	100	358	500	72	590	682
Pheating(MW)	50	50	206	70	100	112
Pfus(GW)	0,5	1,8	2,5	0,36	2,95	3,41
Q	10	36	12	5	29,5	30

DIAGNOSTICS and CONTROLS for DEMO

References :

F P Orsitto et al IAEA FEC 2014 St Petersburg paper p7-8

Conference Diagnostics for Fusion Reactors , Varenna september 2013

F P Orsitto et al - EFDA TA DAS04- DEMO Instrumentation and Control –Final Report (july 2014)

MAIN MESSAGES

- **DEMO diagnostics should focus on high priority parameters:** *diagnostics for machine protection and basic control to be useful for **BURN control in long pulses**.*

- **The space available for diagnostics is severely limited by the TBR(Tritium Breeding Ratio) : a minimum set of systems is used to protect and control the machine.**
  The engineering of diagnostics must be inserted in the overall design of DEMO from the Beginning due to the optimization of the space dedicated, compatible with the TBR:
  likely the organization of diagnostics in PORT PLUGS of ITER will NOT be used.

- **The high fluence of DEMO (30-50 x ITER fluence) put the other important constraint** on the diagnostics: in practice the ITER diagnostics MUST BE REVISITED BECAUSE OF THE HIGH DPA IMPLIED IN DEMO OPERATIONS.

- Diagnostics (nearly) feasible (low extrapolation from ITER design and R&D needed)
  Microwave (and Far Infrared Light) techniques
  Direct line-of-sight techniques (neutrons, x-rays)

Strategy for diagnostics/control optimization

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Two phases of work can be envisaged on DEMO :

I) ITER-like phase : assessment of control of Q>>10 scenario and control/training of prediction codes;

- BURN CONTROL in conditions where P_{alpha}/P_{input} ~7 is *UNIQUE* to DEMO
- The ***training*** of transport/prediction codes for Control will imply the use of diagnostics set similar to ITER

II) Power-plant phase : TBR >1.1 constraint , severely limits the access and minimum set of diagnostics must be used + codes

Environmental conditions

Environmental conditions more extreme than in ITER (>100 times higher neutron fluence):

- No electrical and refractive components close to the plasma
- Limited application for first mirrors

Very limited access possibilities

Large emphasis on

- Reliability, Maintainability, Robustness

Needs:

- Development programme for new materials
- Testing under DEMO conditions

T Donne

ITER-LIKE phase experience

In the ITER-LIKE phase two classes of outputs are **EQUALLY** important :

FIRST CLASS : Plasma operation quantities to guarantee the SAFE and optimal operation

1. Control of the burning Q>>10 phase (for the pulsed device including ramp-up, flat top and ramp down)
2. the divertor power loads and detachment
3. disruption avoidance and mitigation
4. The simulation and control codes

SECOND CLASS: subsystems monitoring and safety

The diagnostics of the subsystems of the device include :

i) Blanket modules
ii) Heating systems
iii) Wall erosion and damage monitoring
iv) Dust measurements
v) Creep-fatigue monitoring (*pulsed DEMO*)

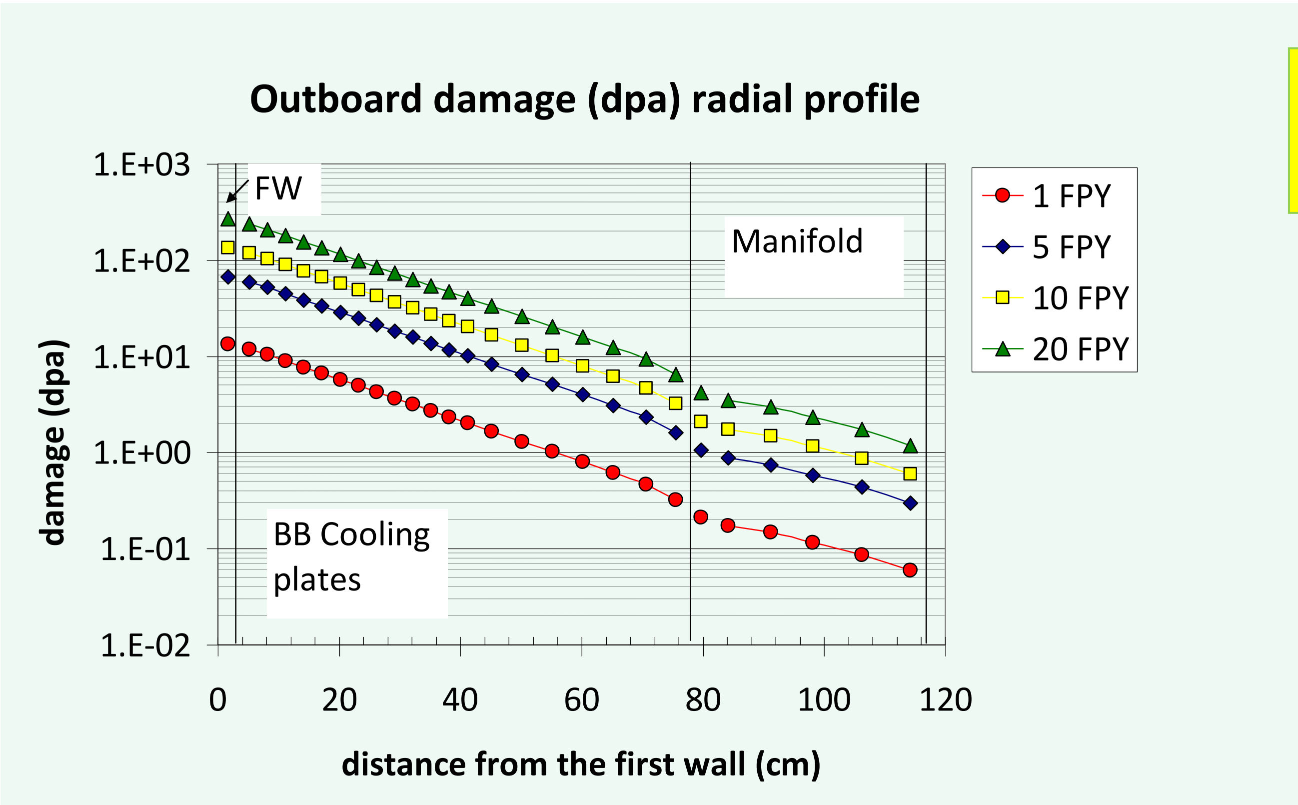
Comparison of Surface Occupation (TBR ≥1.1)

Areas (m^2)

Machine	Diagnostics	Heating and Current Drive
JET	10	3 + ICH antennae (internal)
ITER	36	26 (includes HNB3 and LH)
DEMO	3-5	6-10

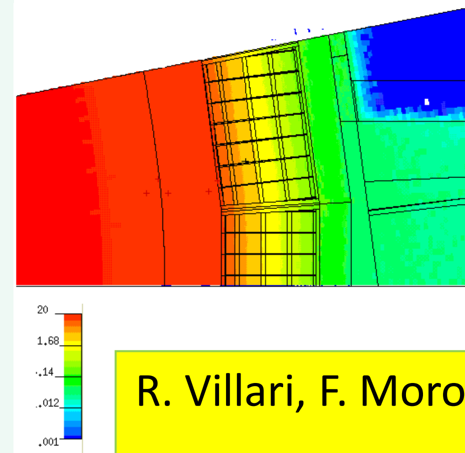
P Thomas

NEUTRON DAMAGE on DEMO1



Eurofer m2 in Manifold

SS316 m40 in VV



R. Villari, F. Moro

PPPT WP12-DTM04

From the neutronics calculation :
Approx the level of damage calculated for ITER lifetime (i.e. 3dpa)
Is found in DEMO at 0.5m from the First Wall in 5 full power years .

The First Mirror planned for ITER resistent to 3dpa can be used in DEMO
At a deistance of 0.5m from the Vacuum Vessel .

Consequences of neutronics calculation on FM position

From the neutronics calculation :
Approx the level of damage calculated for ITER lifetime (i.e. 3dpa)
Is found in DEMO at 0.5m from the First Wall in 5 full power years .

The First Mirror planned for ITER resistent to 3dpa can be used in DEMO At a deistance of 0.5m from the Vacuum Vessel .

Short review of FM work so far

At moment Molibdenum(Mo) and Tungsten(W) mirror are considered as FM in ITER
Results for Polarimetry/intefrometry using wavelengths $\lambda \geq 100 \mu m$

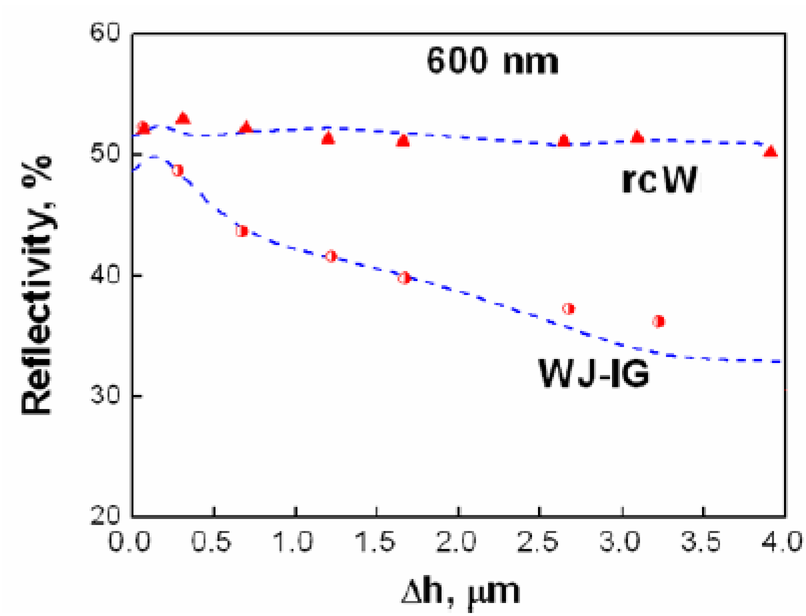
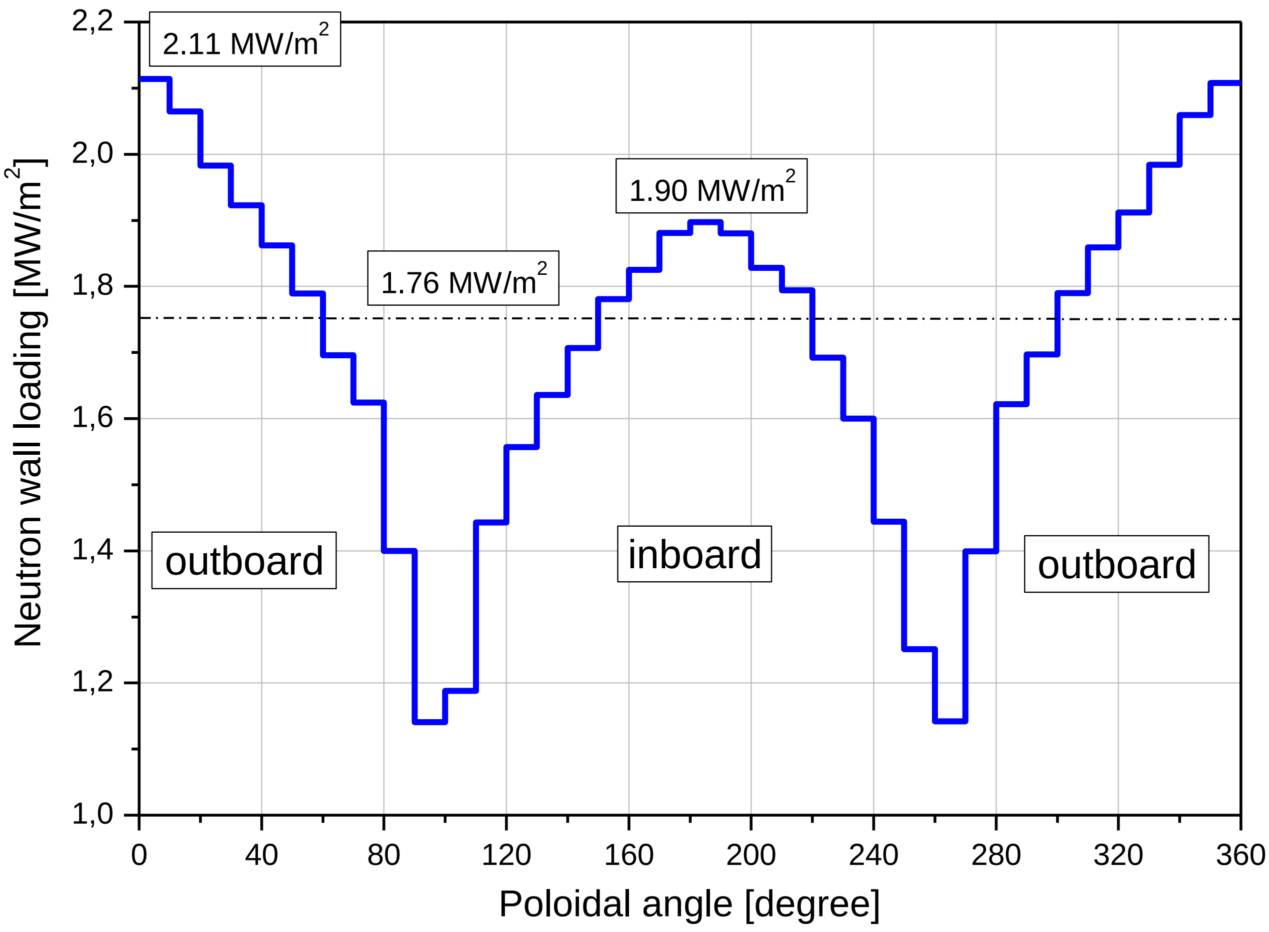


Fig. 5. Dependence of reflection coefficient *on the sputtered layer thickness for WJ-IG and* rc*W mirrors irradiated to 3 dpa (points) and not irradiated (dotted curves) sides at wavelength 600 nm*

Results of irradiation
To 3dpa damage on two samples of W mirrors

V S Voitsenya 2013

Example of Poloidal profile of neutron wall loading



In the vertical ports the neutron flux is close to be 50% LESS than the equatorial OUTBOARD ports

Classification of diagnostics for DEMO

- machine protection
- Basic control
- ADVANCED CONTROL (ITER-like phase)

machine protection	basic control	advanced control (*)
disruption	equilibrium	alpha part measurements
heat loads	burn control (Te control)	current profile
alpha losses	MHD control/CD control	kinetic profiles (pedestal)
density control	ELM mitigation	
plasma position	Radiation control	
fusion power	kinetic measurements	
radiation profiles	divertor control	
magnetics equilibrium (MHD markers)	Burn control (fuel and fuel ratio control)	

(*)Not working in power plant phase

Diagnostic systems FOR MACHINE PROTECTION

Minimum set of dia for Machine protection(R&D needed) :

Magnetics (Hall sensors to be tested at high dpa>3,
Low Temperature Co-fired Ceramic (LTCC)technology under test for ITER??)

IR Cameras (W or Mo mirrors to be tested for dpa>3)

Polarimetry (W or Mo mirrors to be tested for dpa>3)

Position reflectometry (ITER reflectometry nearly OK)

Fission chambers(ITER fission chambers to be qualified)

X-ray spectroscopy (X-ray mirrors and/or policapillary lenses to be tested)

VUV and Vis spectroscopy (*)(W or Mo mirrors to be tested)

R Felton

(*) using monitors of W emission close to 5nm , containing the quasi-continuum emission W 27+ - W 35+ and spectral lines at 0.794nm emitted by W 46+

Magnetics

For ITER levels of exposure, parasitics are already dominated by sensor effects.

- Electronics for 12h pulses are demonstrated, but in-vessel sensors, although they could survive, have excessive drift

DEMO R&D should *concentrate on robust and drift-resistant sensor packages*

Placement of the sensors is extremely important: need locations with good poloidal flux penetration.

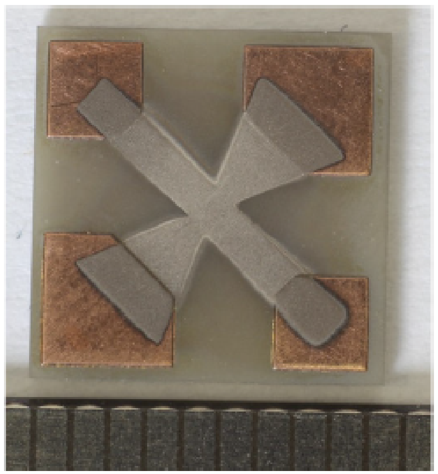
For parasitics at the level of the ITER sensors, DEMO will definitely need steady-state measurements to compensate for drifts, ideally in-vessel

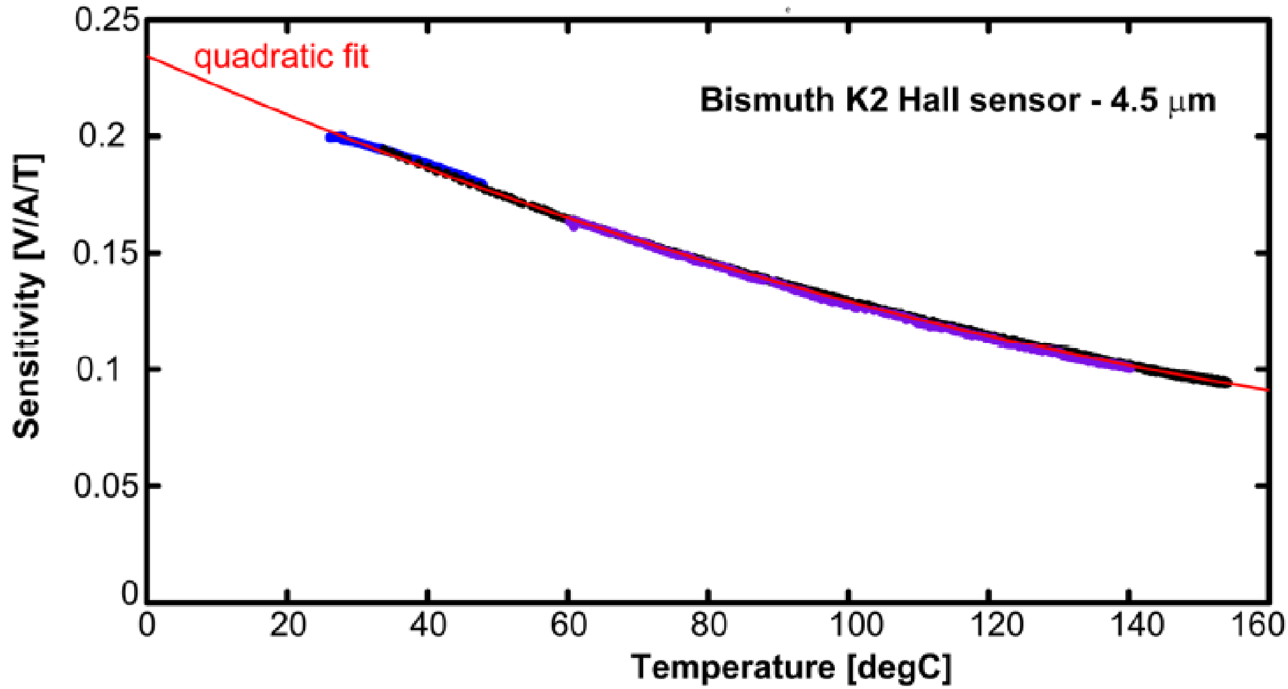
- **Most promising technology is metallic Hall probes .**
- **For shape control, ITER may also well prove plasma position reflectometry** is adequate, but this will require dedicated space allocation

Cabling is as important as the sensors: similar effects and harder to des
maintain

G Vayakis

HALL sensor example





- Success in using Gen 2 DBC technology also for bismuth sensing layers.
- No problem with noise (up to ~150 degC) – noise level about the same as for Cu while, signal is ~2000 times higher.
- Significant loss of sensitivity with rising temperature – quadratic dependence.

I DURAN

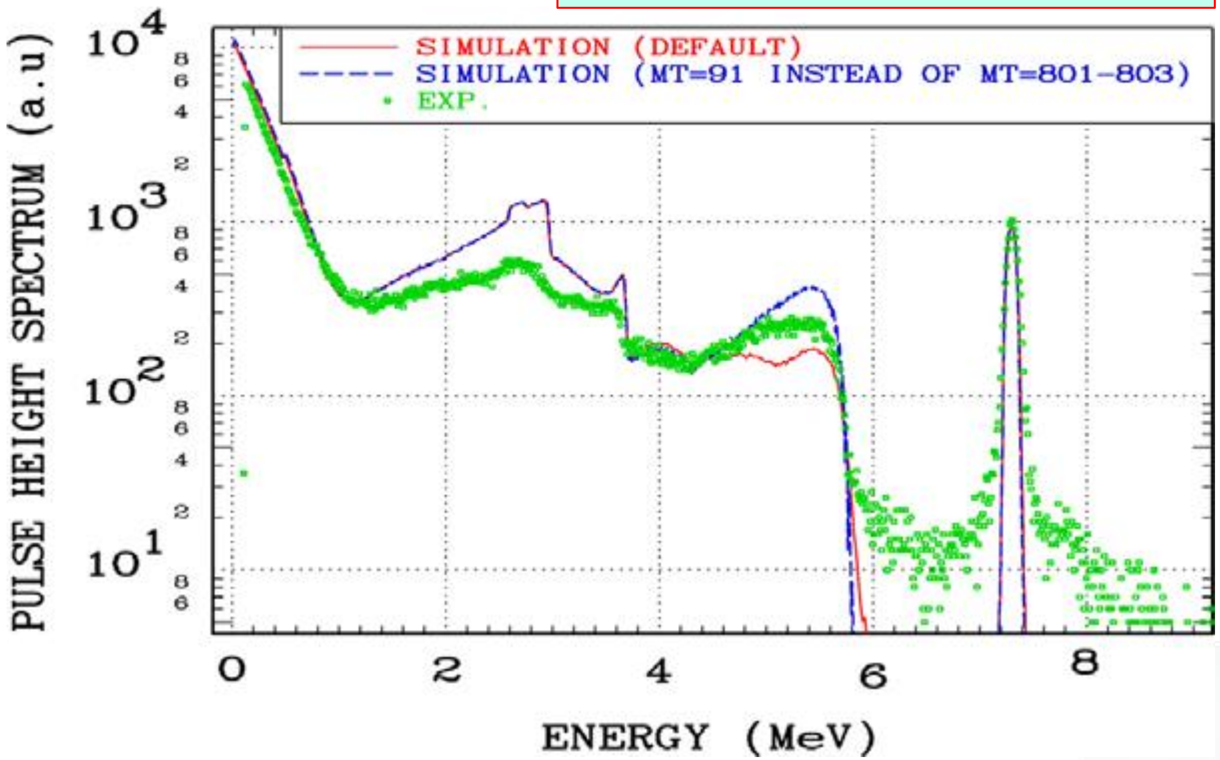
Neutronics

Diamond detectors

Candidate detector for ITER n camera:
Very robust material
Temperature resistant
Radiation hard
Fabrication CVD

G Ericsson

M Pillon(2011) , Milocco(2013)

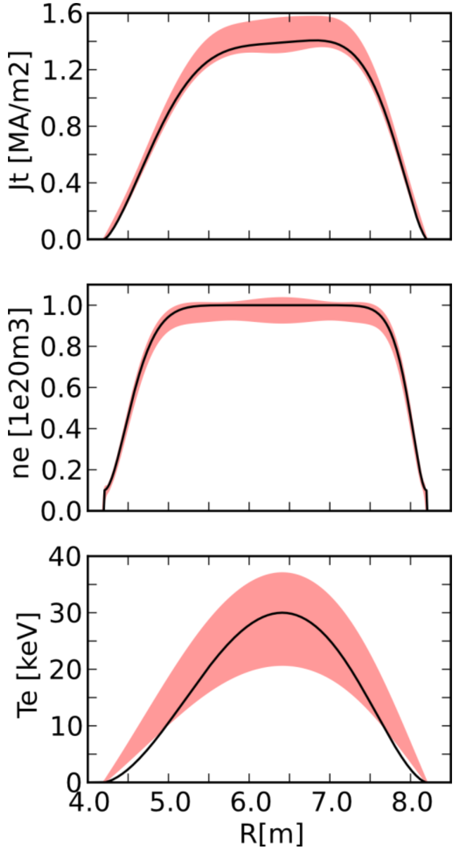


EUROfusion

POloidal POLArimetry

ENEA AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

Error of $\Delta\theta$: 0.1 degree[4]
Error of $\Delta\varepsilon$: 0.6 degree[4]

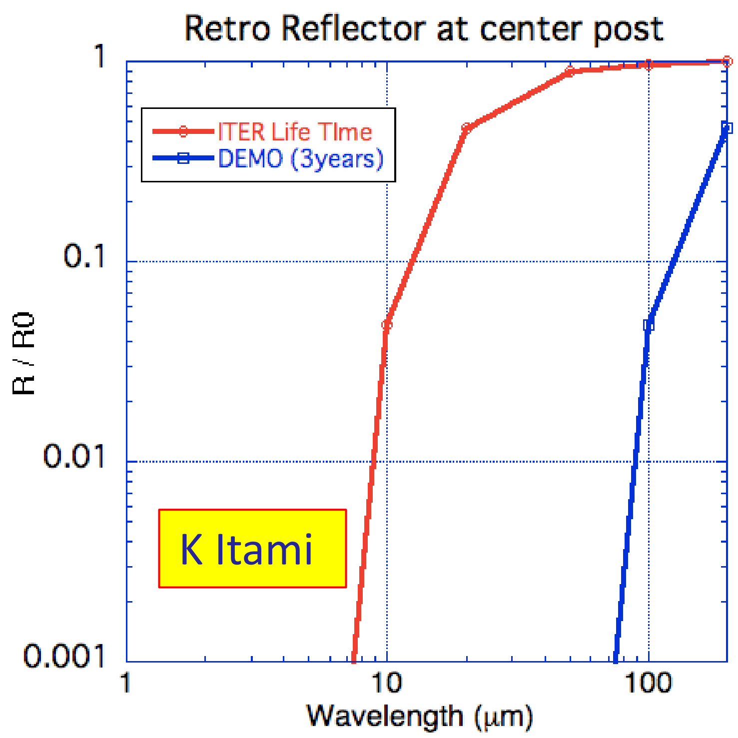


15 viewing chords, 119 µm

Faraday Rotation Measurement Is Promising method in Future Reactor Due to High Resistance to Mirror Degradation

Imazawa

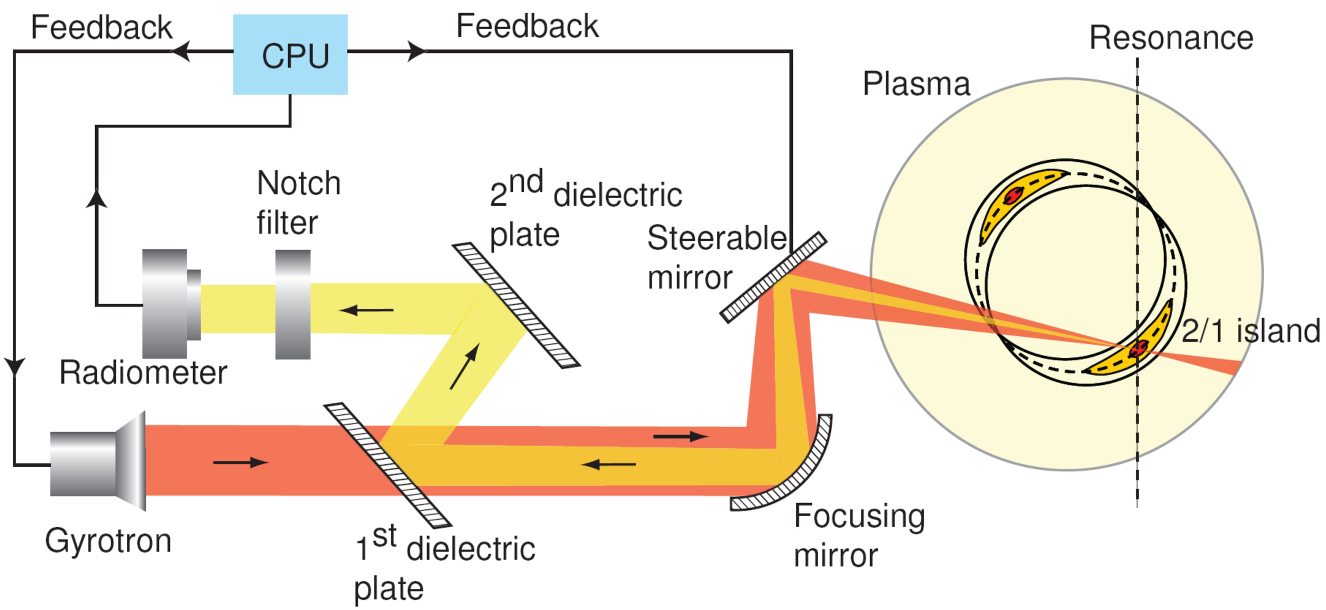
ITER :Measurements of Density (error 8%) and Temperature(error 30%) possible by polarimetry



MHD CONTROL

- In-Line ECE: Integration of ECE system in ECCD Transmission Line. Notch around gyrotron frequency
- Co-located system
- Two implementations
  - TEXTOR (Quasi Optical)
  - AUG (CW, waveguides)
- Good news for DEMO
  - Plasma equilibrium not needed for NTM suppression

M de Baar



BURN CONTROL

$$P_\alpha \approx C_\alpha \; f_{MIX} (nT)^2 \; V$$

$$P_{alpha} = C_\alpha \left\langle ne^2 \right\rangle \overline{\sigma v} \; E_\alpha \; V \, \gamma (1-\gamma)$$

$$\gamma = \frac{n_T}{n_D + n_T}$$

$$C_\alpha = dilution\ factor = (1 - 2 f_{He} - Z_{Ar} fAr - Z_{Be} fBe)^2 \; (ITER)$$

$$P_{loss} (W/m^3) \approx \frac{nT}{\tau E} \approx n^{1.91} * T^{3.26}$$

$$P_{RAD} \approx P_{Brem} \approx Zeff \; n^2 \, T^{1/2}$$

$$\tau EIPBy2 \approx n^{-0.91} * T^{-2.26}$$

Close to ignition

$$for \; P_\alpha \approx Ploss \Rightarrow C_\alpha \; (nT)^2 \approx n^{1.91} * T^{3.26} \Rightarrow$$

$$T \approx C_\alpha^{\;0.8} \; n^{0.07} \; f_{MIX}^{\;0.8}$$

$$P_{fusion} \approx 5 * C_\alpha^{\;2.6} \; n^{2.14} \; f_{MIX}^{\;2.6}$$

In general BURN CONTROL is :
Density Control
Impurity Control
Temperature Control
ISOTOPIC MIX CONTROL

To control the Teq the sensible parameters are: f_{MIX} and C_α.

To control the burn the sensible parameters are : ne, f_{MIX} and C_α.

A tolerance of 10% *in Pfus implies the possibility of changing*

$$\frac{\delta ne}{ne} \approx 5\%, \; and \; \frac{\delta f_{MIX}}{f_{MIX}} \approx 4\%$$

$\Rightarrow$ *the accuracy needed for measurement of density is* 1–2%

$\Rightarrow$ *the accuracy needed for measurement of fMIX is* 1%.

$\Rightarrow$ *A tolerance of* 10% *in the burn temperature implies the capability of changing the* f_{MIX} *and dilution* C_α *by* 12.5%

Diagnostics for Burn Control

tecnical specifications	diagnostics for	BURN CONTROL		
	accuracy	space resolution	time resol	systems
Te (bulk)	5%	a/10	<100ms	ECE (Polarimetry)
ne	1%	a/10	<100ms	polarimetry , reflectometry
impurities	10%	integral	<100ms	VUV-Xray spectr????
Zeff(line int.)	<20%	integral	<100ms	vis spectr ????
Pfus	10%	integral	<100ms	neutronics
confined fast ions	20%	a/10	100ms	NPA
nD/nT	10%	a/10	<100ms	NPA
core He density(nHe/ne)	10%	a/10	100ms	??
Ti(bulk)	10%	a/10	100ms	neutronics

Minimum set of Dia BURN CONTROL:

- ECE
- Magnetics
- Reflectometry
- Polarimetry
- Neutronics
- VUV spectroscopy
- Vis spectroscopy
- NPA

EUROfusion

Readiness level of neutron diagnostics for DEMO

ENEA
AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

TRL 1	Basic principles observed and reported.
TRL 2	Technology concept and/or application formulated.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept.
TRL 4	Technology basic validation in a laboratory environment.
TRL 5	Technology basic validation in a relevant environment.
TRL 6	Technology model or prototype demonstration in a relevant environment.
TRL 7	Technology prototype demonstration in an operational environment.
TRL 8	Actual Technology completed and qualified through test and demonstration.
TRL 9	Actual Technology qualified through successful mission operations.

System	Likely detector	TRL (after ITER)	Justification
Neutron flux monitor system	Fission chambers	7	Used extensively on JET and other tokamaks, planned for ITER, main question is DT calibration accuracy
Neutron camera system	Scintillators, TOF	6 (7)	Used on JET,MAST etc, planned for ITER, Near the plasma the system is mostly passive i.e. limited mechanical parts Number of lines of sight and detector choice are crucial to maximise number of measurable parameters and accuracy of results

S Lilley

Planning of R&D for Diagnostics

The planning of R&D must take into account that

i) a programme including the selection of tests of minimum set of sensors and control schemes must be carried out on ITER , JT-60SA and other devices available before DEMO comes into operation

ii) the use of codes like TRANSP or/and METIS for DEMO control can be started in the context Of ITM(International Tokamak Modelling) activity

Demo DIA MACRO-AREAS

1. Burn control : DIAGNOSTICS FOR ALPHA PARTICLES , PLAMA TEMPERATURE, FUEL MIX

2.TRANSPORT CODES AND SINTHETIC DIAGNOSTICS : AN example is METIS CODE

3.Radiation hardening of diagnostics to be used continuously During the Power-plant-like phase

R&D AND NEW CONCEPTS

R&D NEEDS in DIAG Technology	new concepts of diagnostics TO BE DEVELOPED
magnetic sensors	LOST FAST PARTICLES
mirrors /schutters /cleaning techniques	MAGNETICS
bolometers	CURRENT PROFILE (DIFFERENT FROM POLARIMETRY)
X-ray sensors	SPECTROSCOPY :X-RAY , VIS SPECTROSCPY
IR cameras	confined fast particles

Tests on JET

1.Diagnostics for fast (alpha) particles

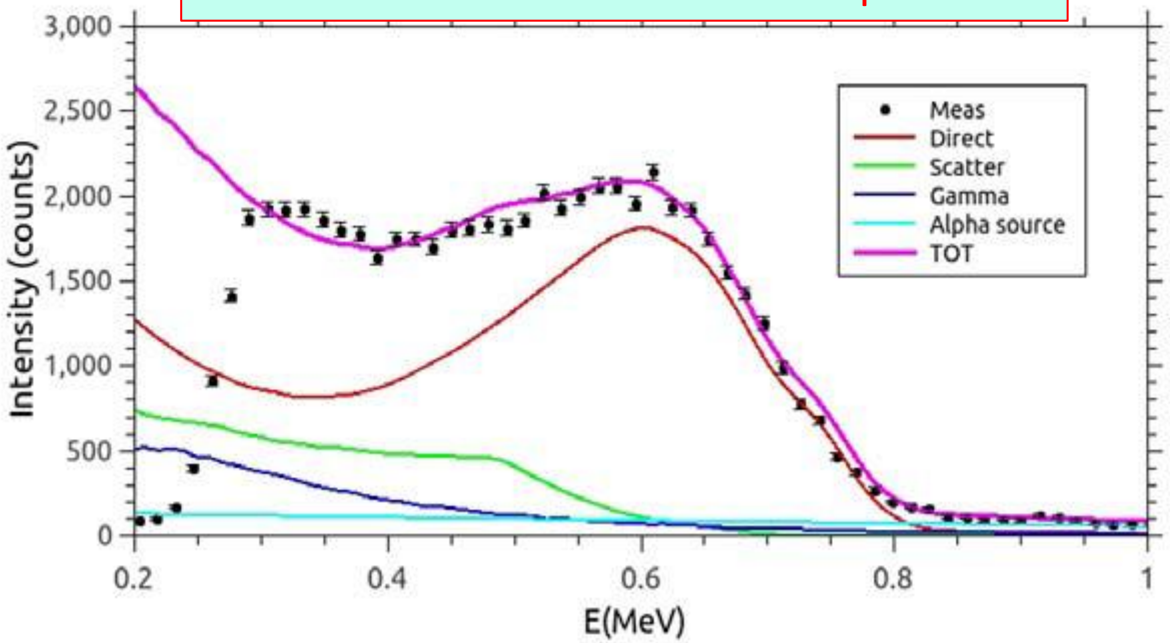
2.Neutron absolute calibration methods

3.Neutron and gamma spectroscopy : new diamond (or SiC) detectors for neutron spectroscopy

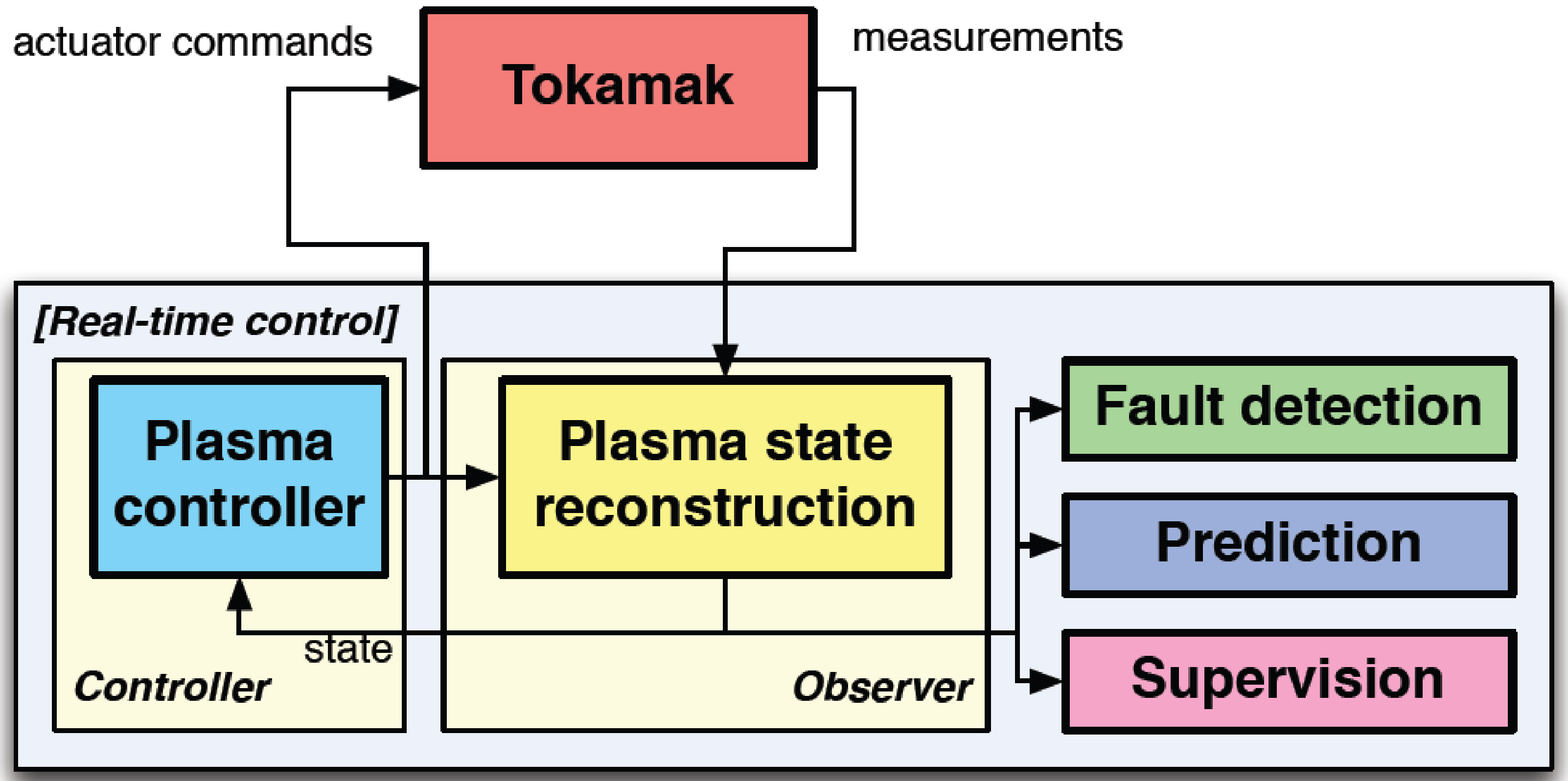
4.Low and High energy Neutral Particle Analyzer(JET High-Energy NPA measures the energy distribution function of neutral H, D, T, 3He and 4He in the energy range 0.3 – 4 MeV.)

5.Neutron absorbers for gamma ray spectroscopy

Diamond detector meas and interpretation



Test on TCV



- **Fault detection**
  - **Detect sudden deviation of measurement from model prediction**
  - **Isolate fault and exclude from reconstruction**

F Felici

Conclusions

The elaboration of DEMO device parameters and concrete implementation
Is now one of the objectives of fusion community

The DEMO models are now moving in the direction of a long pulse (3-4hours) device
With main inductive current

R0=9m BT=6.5T Ip=17MA A=R0/a=3.6

Diagnostic systems need to be used for the control of burn and machine protection only

String R&D is starting : key point is resistence of the components to the high Neutron Fluence

Minimal set of diagnostics for DEMO control includes :
IR systems (reflectometry, polarimetry)
Neutronics (neutron /gamma cameras)

R&D needed in Mo and tungsten mirrors
Development of control codes based on physics models