New Trends in Fusion Research

Ambrogio Fasoli

Centre de Recherches en Physique des Plasmas

Ecole Polytechnique Fédérale de Lausanne

and MIT –USA

CERN Academic Training Programme

11-13 October 2004

Credits and acknowledgments

EFDA, CRPP, MIT-PSFC, PPPL, LLNL, SNL, IFE Forum, US-DoE, ILE Osaka, ESA, NASA, LLE, UCB, UKAEA, ….. with

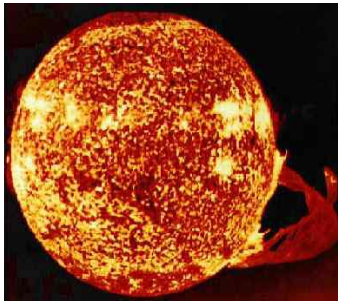
apologies to the many authors from whom I have 'stolen' viewgraphs

Lay-out of Lecture 5

- Burning plasma physics
  - Wave-particle interaction and self-heating
  - Experiments on the JET tokamak
  - Burn control
- ITER: the world burning plasma experiment
  - Main goals and parameters
  - Design
  - *A fast track for fusion?*

Fusion plasma *physics* challenges

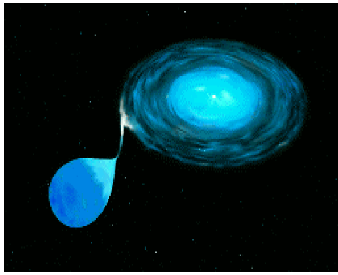
- Large power density and gradients ($10MW/m^3 \approx 30'000\times$sun's core), anisotropy, no thermal equilibrium
  - Macro-instabilities and relaxation processes



solar flares, substorms

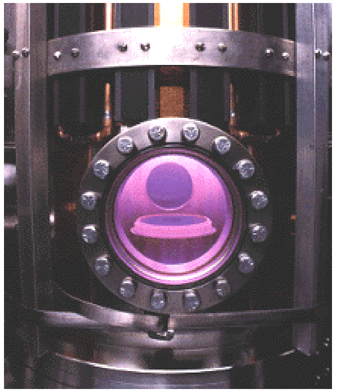
- Dual fluid/particle nature
  - Wave-particle interaction (resonant, nonlinear)

coronal heating



- Turbulent medium
  - Non-collisional transport and losses

accretion disks



- Plasma-neutral transition, wall interaction

plasma manufacturing

Huge range in temporal ($10^{-10} \rightarrow 10^{5}$ s) and spatial scales ($10^{-6} \rightarrow 10^{4}$ m)

Definition of a burning plasma

- Fusion power density ≡ $P_{fusion} = \frac{1}{4} n^2 \langle\sigma v\rangle E_{fusion}$ ($n_D = n_T = n/2$)
- α power density ≡ $P_\alpha = 0.2\ P_{fusion}$
- Thermal energy $W \equiv 3nT$
- Energy balance

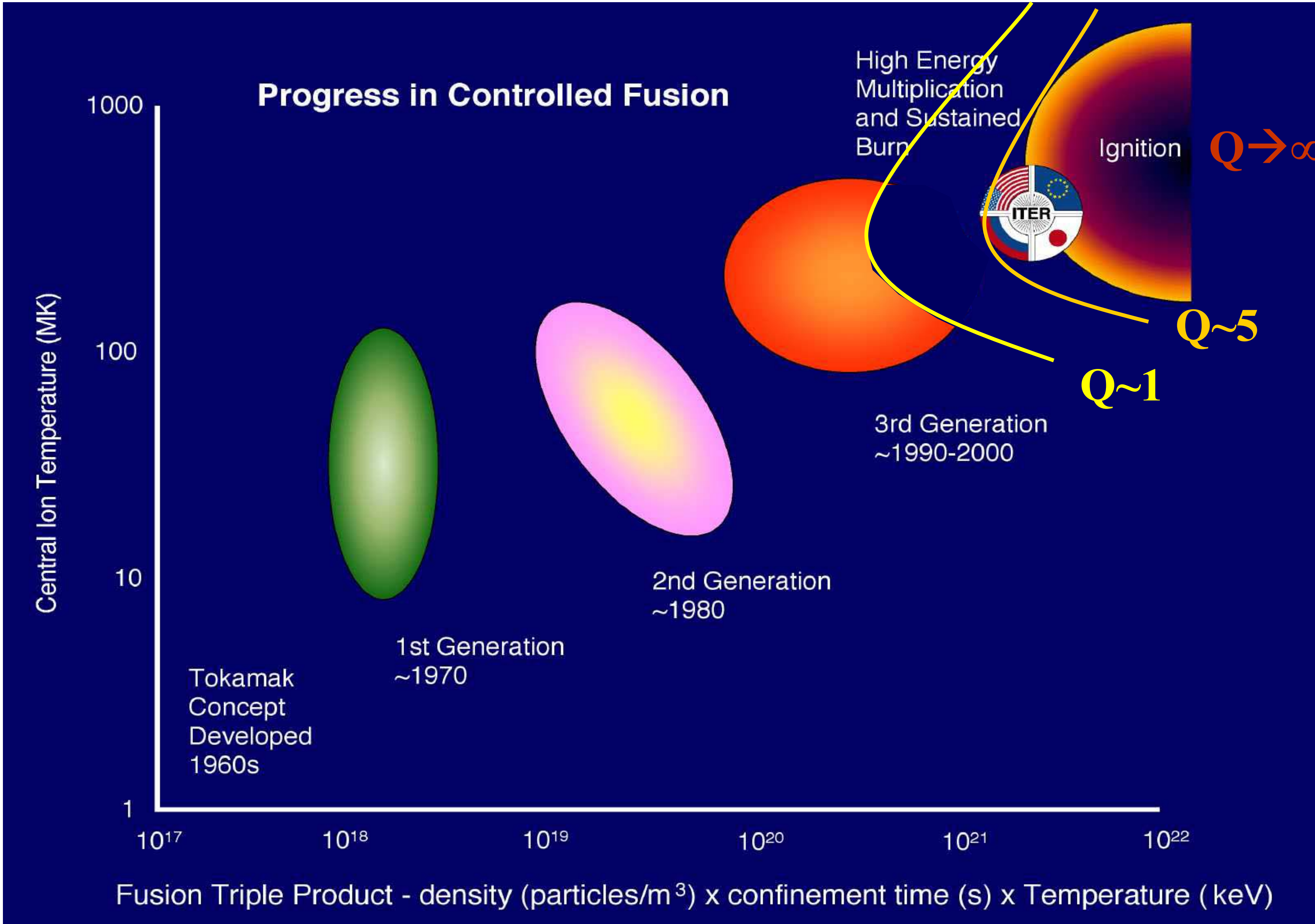
$$dW/dt = \underbrace{P_\alpha}_{\alpha\text{-heating}} + \underbrace{P_{heat}/V}_{\text{ext. heating}} - \underbrace{W/\tau_E}_{\text{losses}}$$

- Fusion energy gain: $Q \equiv P_{fusion}/P_{heat} = 5\ P_\alpha/P_{heat}$
- α heating fraction: $f_\alpha \equiv P_\alpha/(P_\alpha+P_{heat}) = Q/(Q+5)$

$Q=1$	$f_\alpha=17\%$ *breakeven*
$Q=5$	$f_\alpha=50\%$
$Q=10$	$f_\alpha=67\%$
$Q=\infty$	$f_\alpha=100\%$ *ignition*

burning plasma (↓ from $Q=5$ to $Q=\infty$)

Progress in magnetic fusion

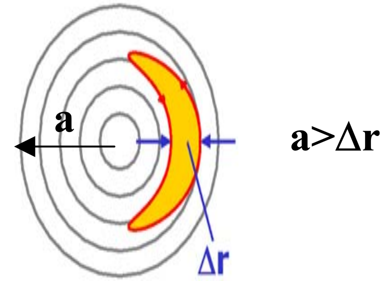


Specific properties of burning plasmas

- Large scale
  - Different scales involved in turbulence: impact on confinement
  - Different kinds of global instabilities
- Large isotropic population of fusion produced α's
  - Effect on background plasma stability, turbulence and transport
  - Strong free energy source for instabilities in ∇p_α
- Dominant source of plasma heating is provided by α's
  - Collisional heating of el. by α's, removal of low energy α's (ash)
  - Nonlinear coupling between α's, plasma pressure profile, pressure driven current, turbulent transport, macro-stability, …
    - Plasma profiles cannot easily be controlled from outside
  - Self-driven burn and thermal stability

Requirements for burning plasma studies

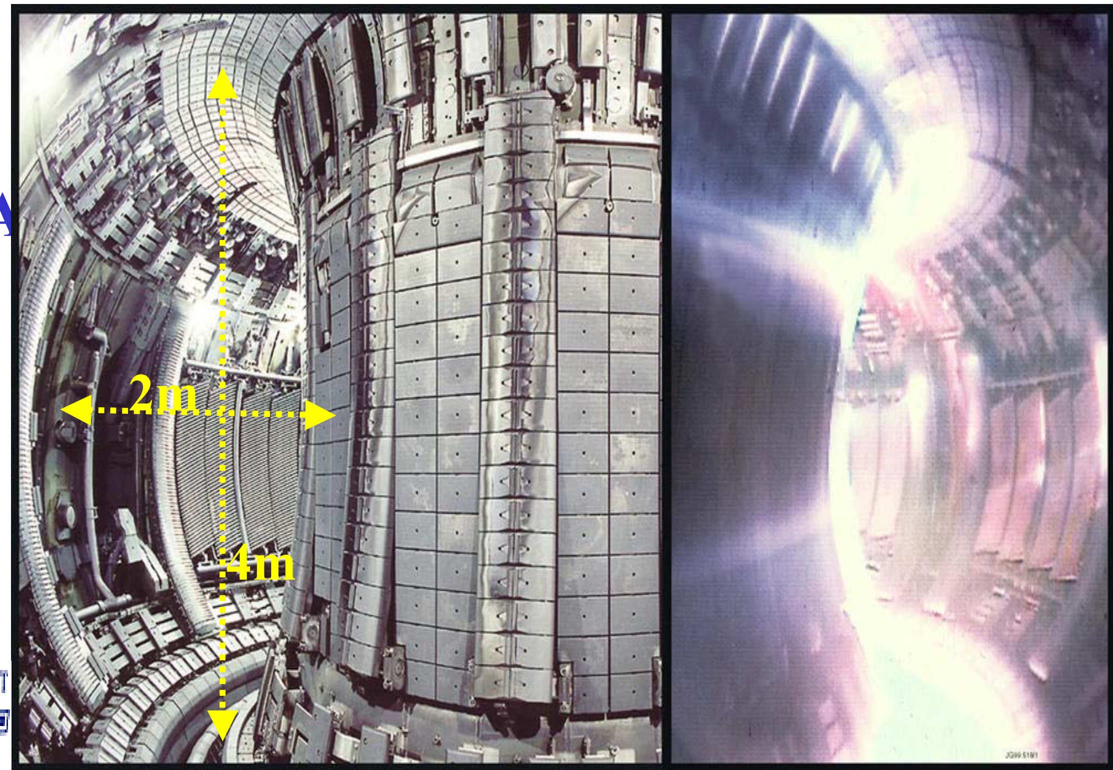
- Capability of generating and measuring fusion α's or other fast ions with similar energies (~MeV)
- Plasma size, I_p, B_T sufficient to confine them in reactor relevant regimes



The JET tokamak

R~3m; B_T^{max}~4T; I_p^{max}~4MA

D, H, He and D-T plasmas

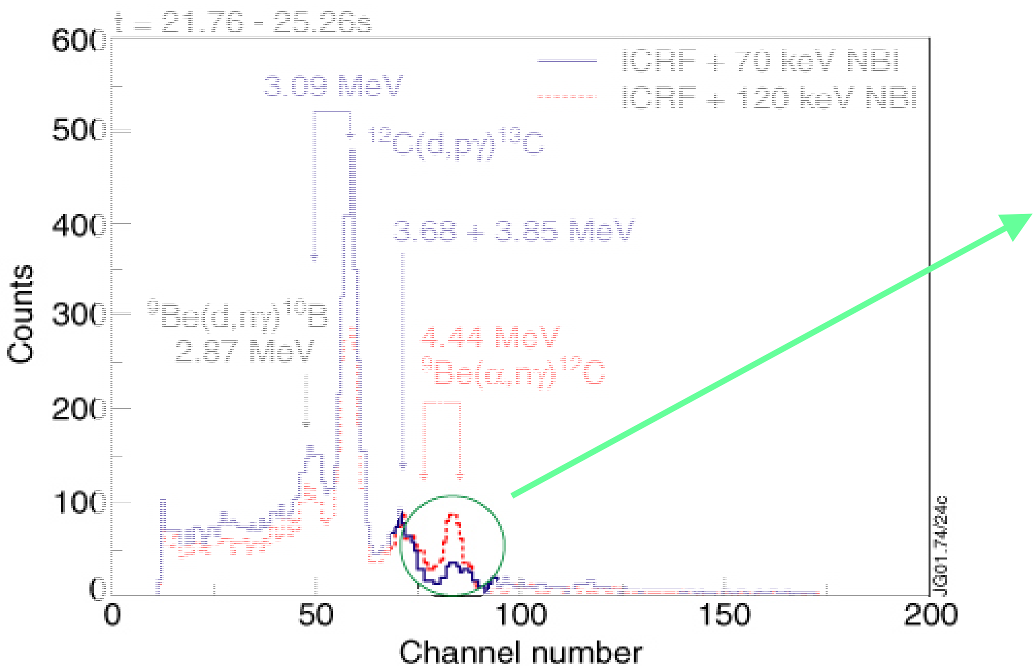


EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

Sources of fast ions in JET

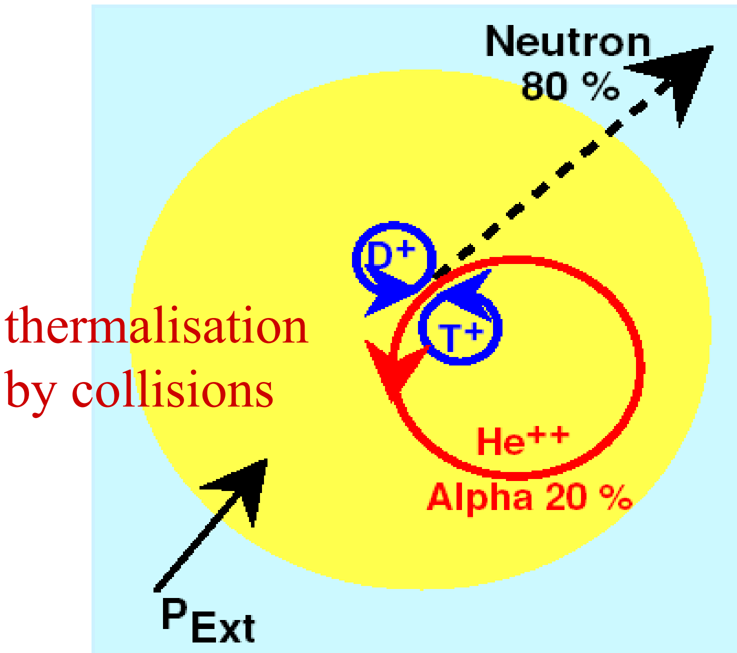
- D-T reactions: 3.5MeV α's
  - Q<1: ∇p_α, n_α < than in burning plasmas
- Ion Cyclotron Resonance Heating: ~MeV ions
  - $P_{ICRH} \leq$ 13MW: ∇p_{fast}, n_{fast} ≥ than in burning plasmas
  - **Ex.: ^{4}He acceleration by ICRH at $f_{ICRH}=3f_{ci}(^4He)$**

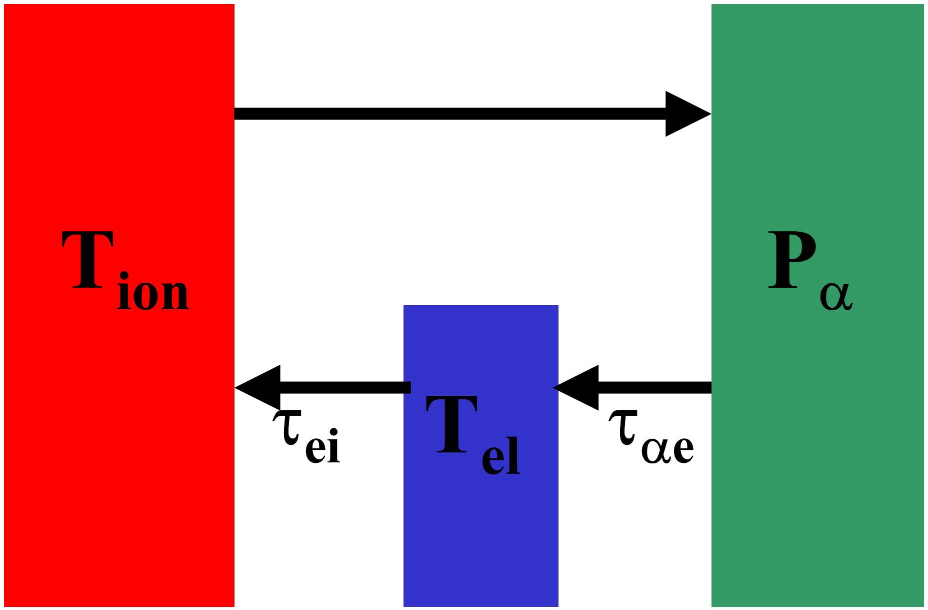
γ-ray emission spectrum



signal from reaction $^9Be(\alpha,n\gamma)^{12}C$
→signature of **^{4}He ions with E_α>~2MeV**

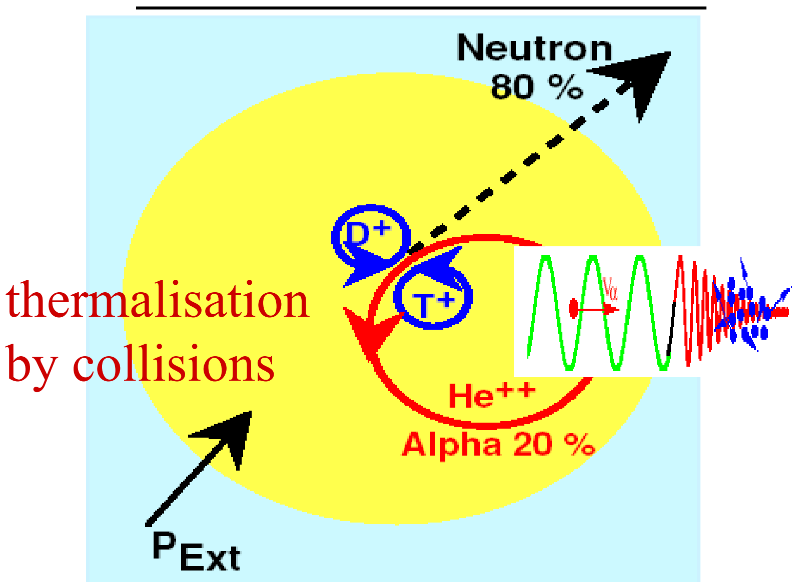
At the core of burning plasma physics: the self-heating process

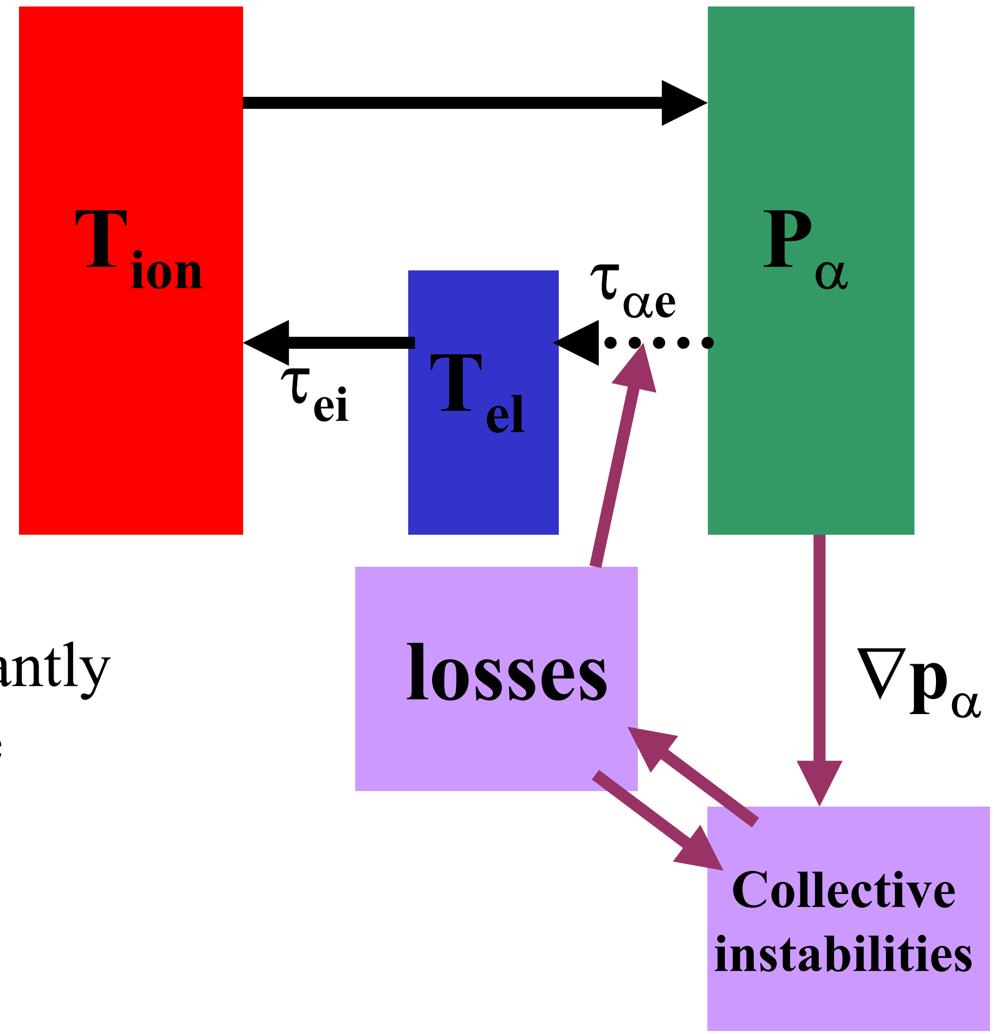




– If α orbits are confined and in the absence of instabilities, α's give all of their energy to electrons (as $T_e \sim T_i$ and $m_e \ll m_i$), which then heat ions

Effect of collective instabilities on self-heating





•If instabilities are excited resonantly by α's and reach large amplitude

→α redistribution / losses

→effect on fusion Q

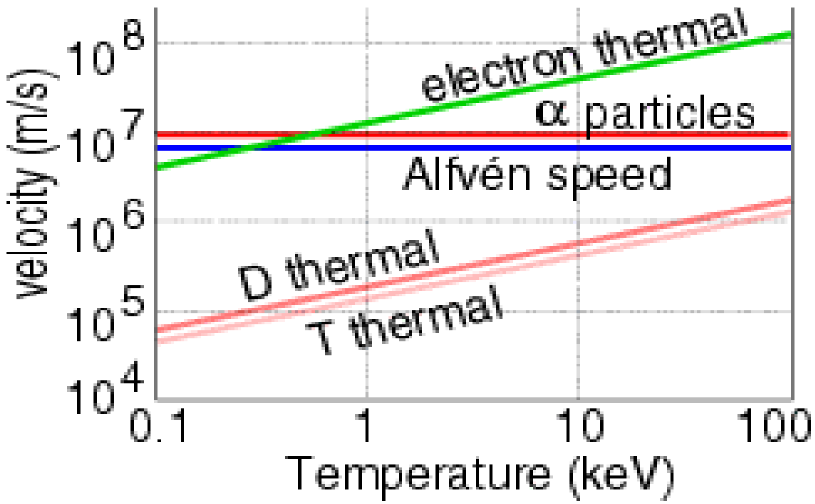
→wall damage

What kind of collective instabilities resonate with α's?

Alfvén waves and Eigenmodes

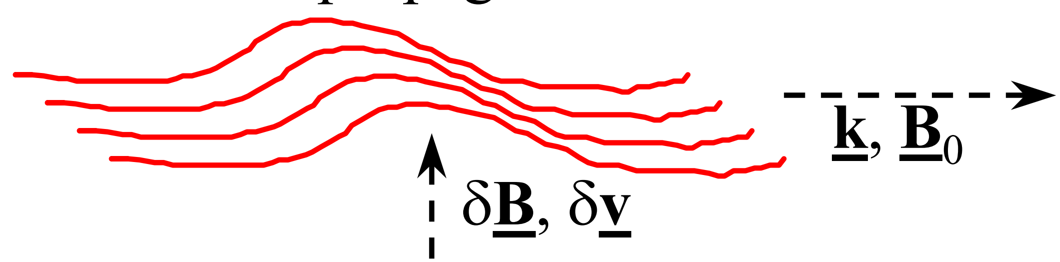
Typical velocities in a tokamak

B=4T; n=10^{20}m^{-3}



- α's resonate with Alfvén Waves
- AWs are driven unstable if
  - → sufficient 'free' energy ∇p_α
  - → α drive > plasma damping

– B-field and plasma frozen together; field lines are strings with tension and inertia → Alfvén wave propagation

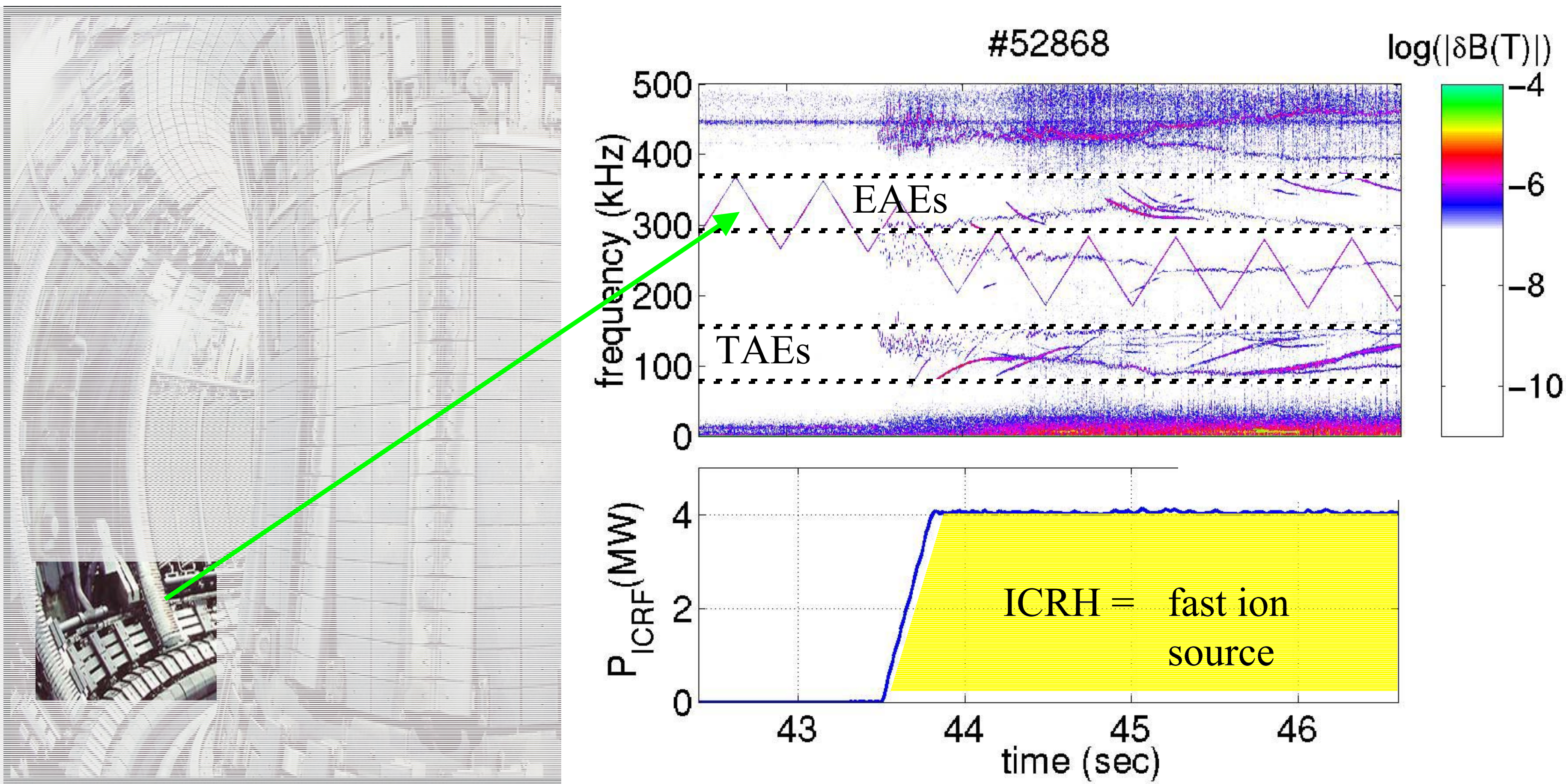


In tokamaks: weakly damped Alfvén Eigenmodes (AEs)

Active and passive spectroscopy of AEs

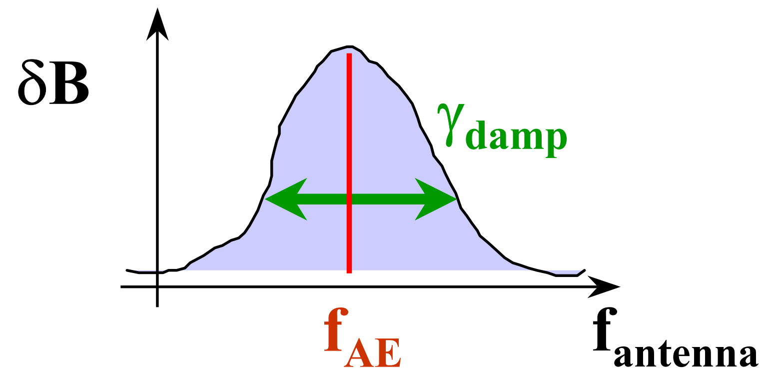
– Passive
  - Modes observed if destabilised by fast particles (NBI, ICRH, *fusion α's*)

– Active
  - In-vessel antennas drive low amplitude perturbations
  - Plasma response measured on B-probes: global modes ← Resonances

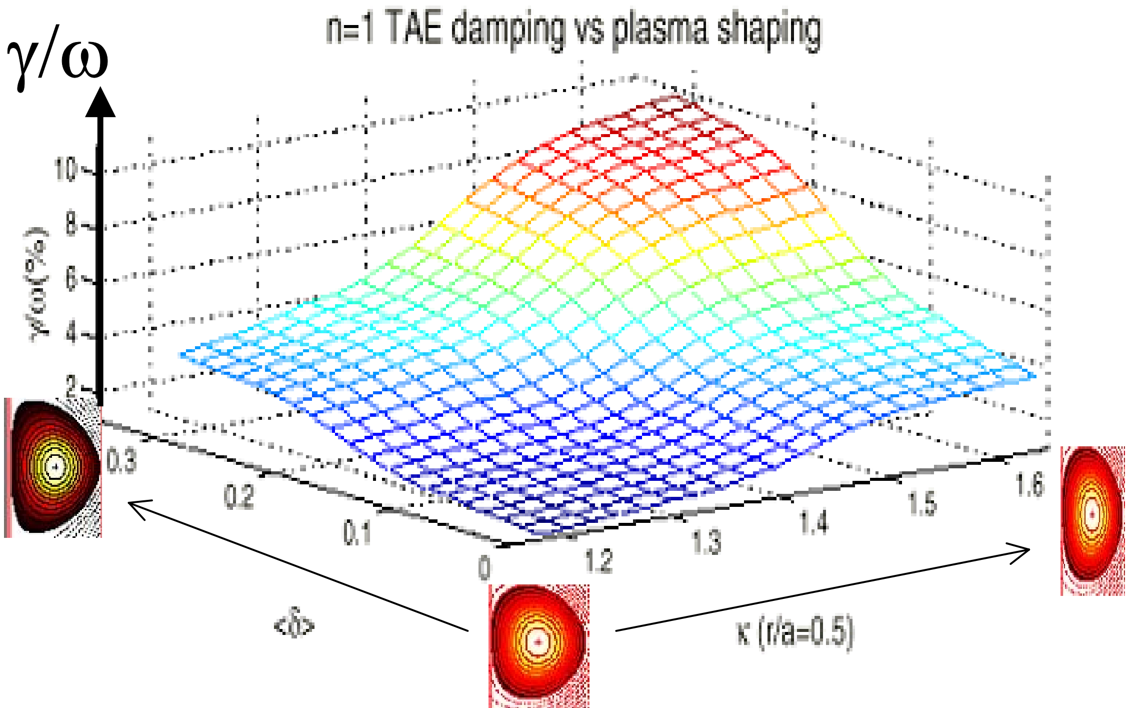


External antenna excitation of AEs

- Measure mode damping rate in the absence of resonant ions
  - understand damping mechanisms
  - conditions for weak/strong damping

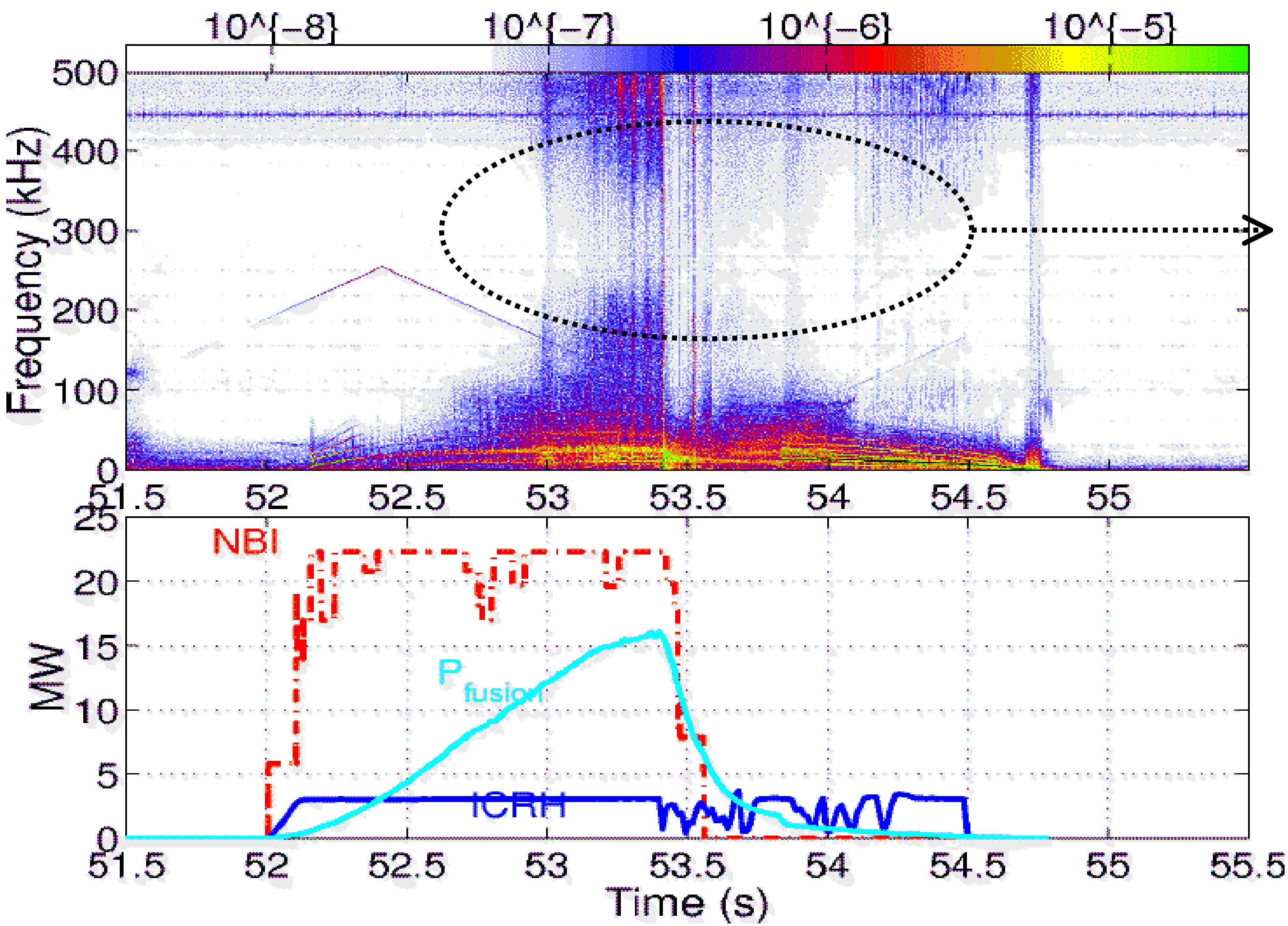


Ex.: effect of plasma shape on damping



Shaping of cross-section → strong damping

No α-driven modes in world record fusion power discharge (P_{fusion}=16MW, Q~0.7)



‘clean’ spectrum in AE range

Collisional α electron heating / slowing down

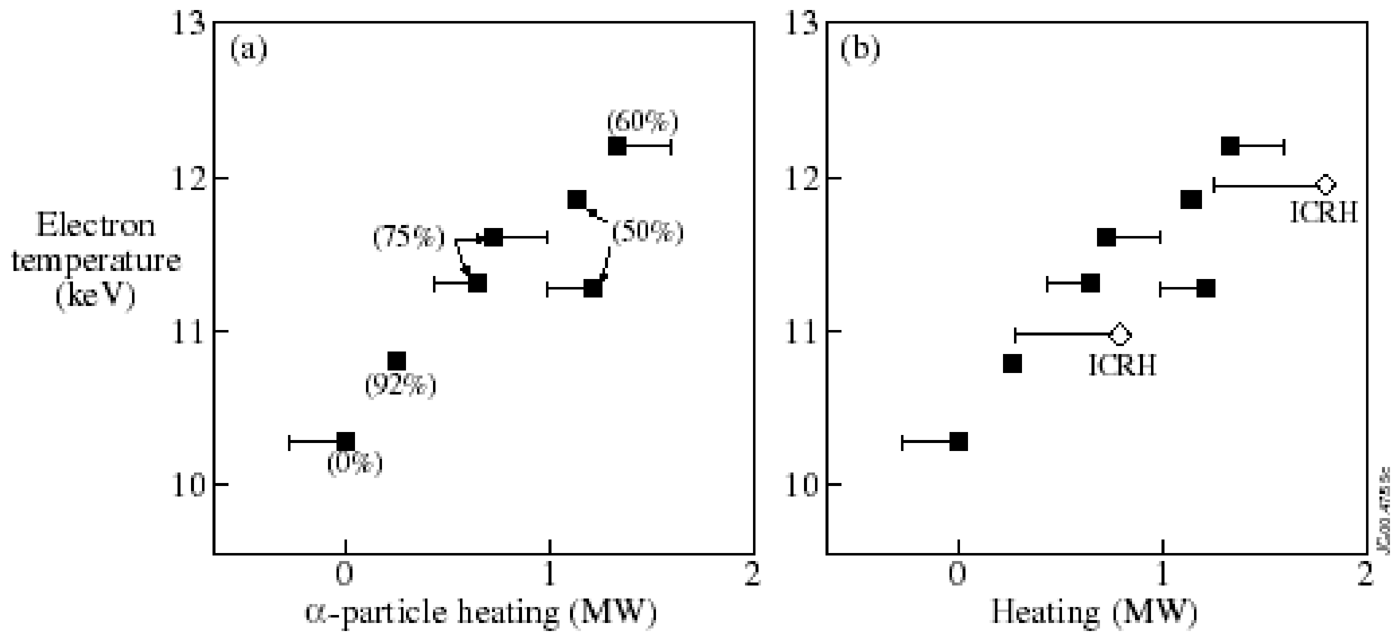
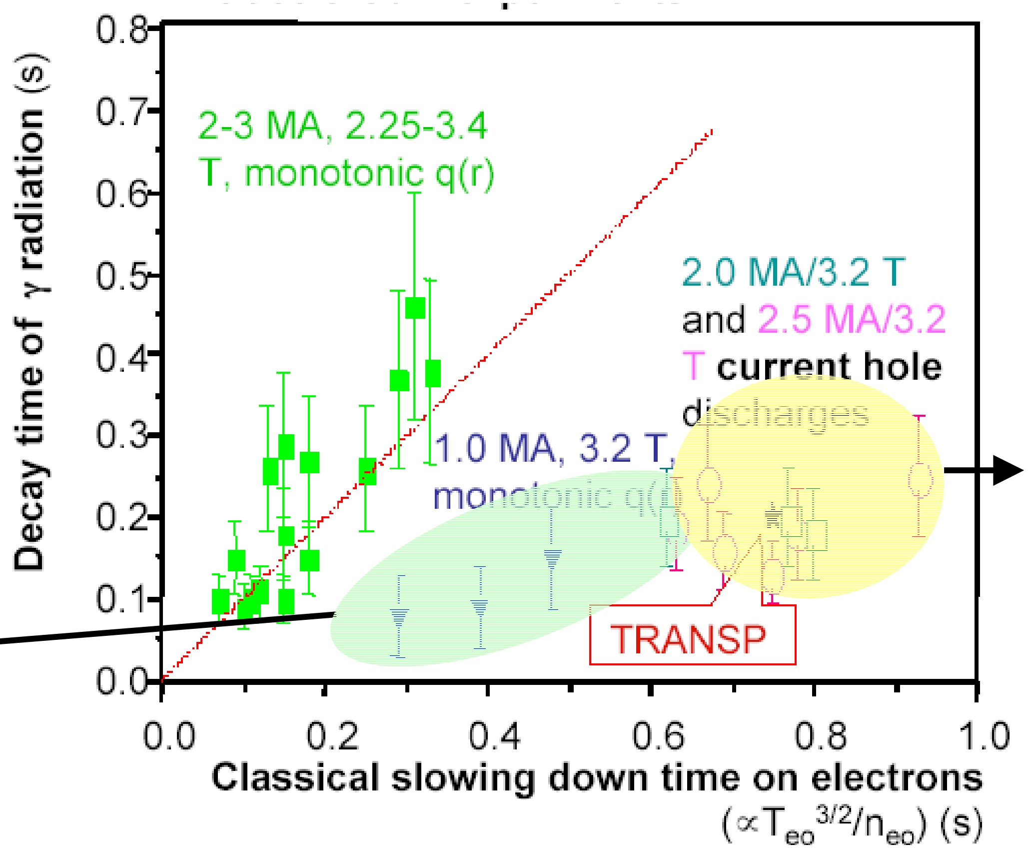


Figure 14.5(a). The fusion α-particles heat the plasma and the resulting increase in electron temperature is clear from the graph, the tritium fractions being shown in brackets. (b) Showing that the α-particle heating is similar to that achieved by comparable ion cyclotron heating of deuterium plasmas.

- Electron heating in D-T (Q<1)
  - No AE instabilities
    - →heating according to collisional theory

Classical slowing-down in the absence of instabilities (Q≤1)

γ-ray spectrometry in trace T experiment



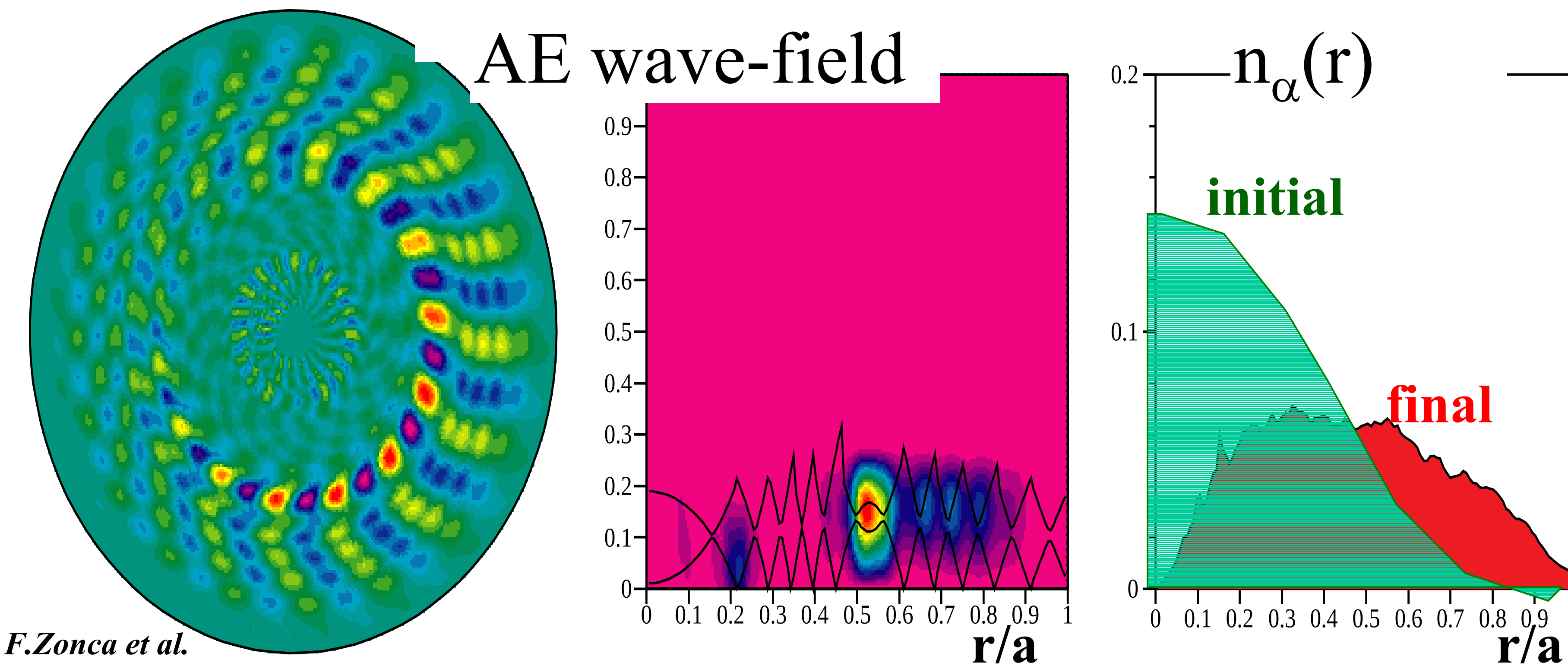
Too low current

Current profile not apt to confine α's *current 'hole'*

Yes, if B-field structure adequate (classical theory OK)

New regimes for AE interaction with α's expected in burning plasmas (Q>5)

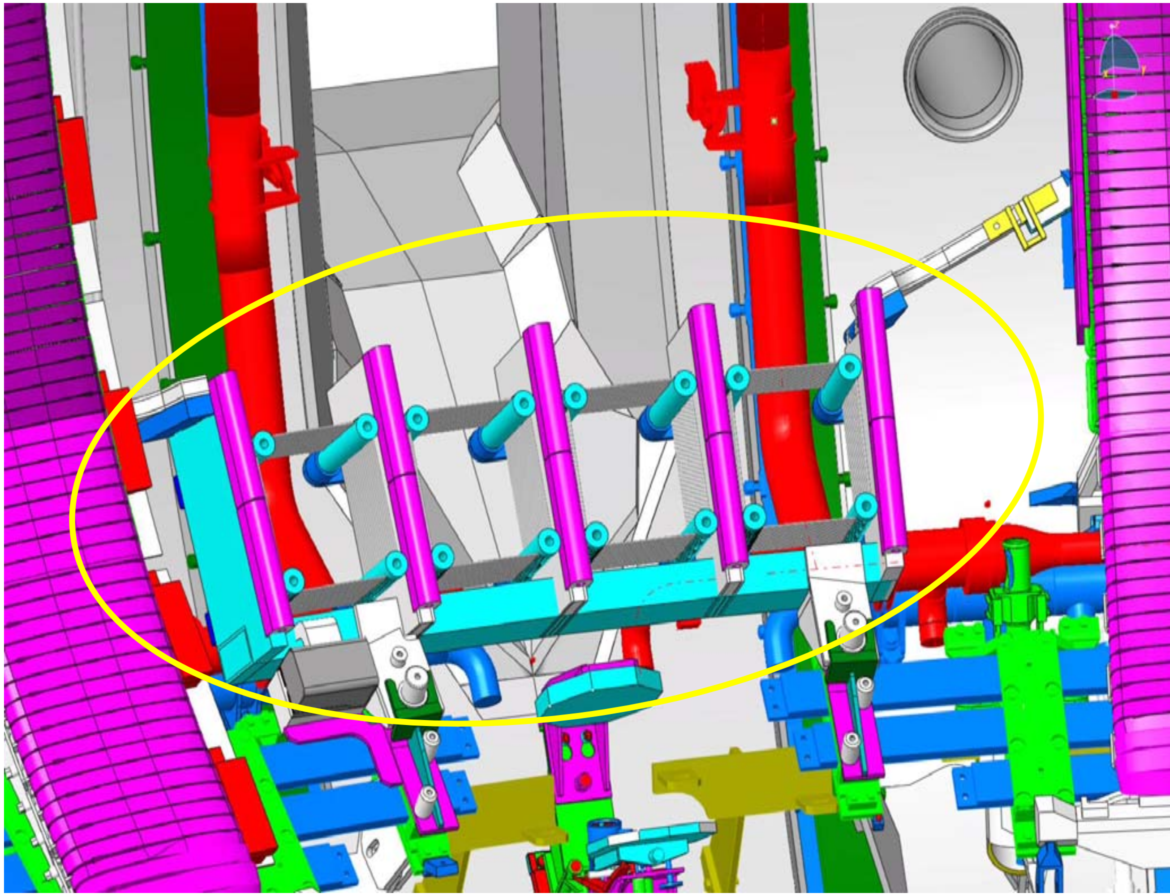
- Large scale (many particle orbits fit in plasma), large ∇p_α
  - 'Sea' of many small-scale, nonlinearly coupled modes
  - **Ex.: Numerical *simulation* of α interaction with many AEs →α redistribution**



New regimes for AE interaction with α's expected in burning plasmas (Q>5)

- 'Sea' of many short wavelength modes
  - **Need new tool to generate and study small λ modes**
  - **New antenna for JET**

CRPP project

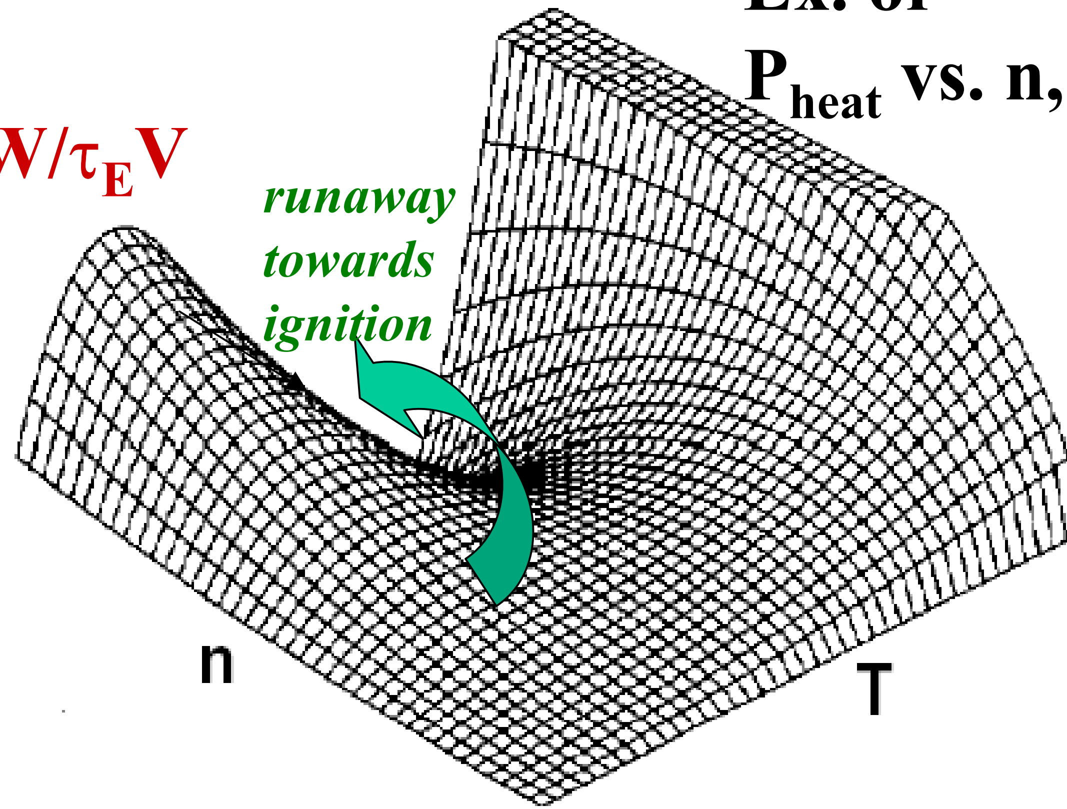


Self-driven burn and thermal stability

Steady-state:

$P_{heat} = \frac{1}{4} n^2 \langle \sigma v \rangle E_\alpha V - W/\tau_E V$

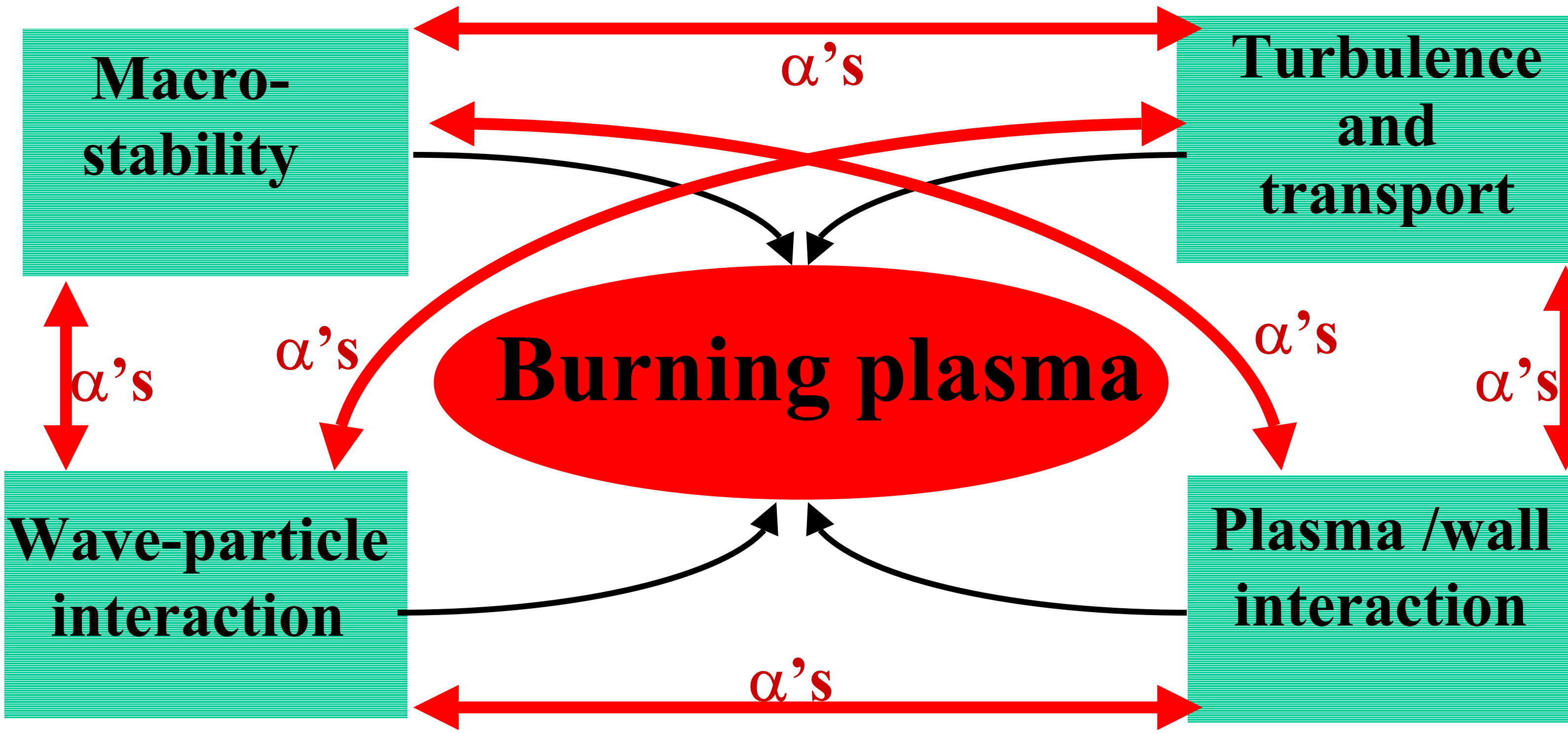
Ex. of P_{heat} vs. n,T



- At large Q, thermal runaway can occur unless
  - $P_{loss} = W/\tau_E$ increases with T more rapidly than $P_\alpha = \frac{1}{4} n^2 \langle \sigma v \rangle E_\alpha V$
  - α's are affected by losses/redistribution ($\tau_{slowing\ down} \ll \tau_E$)

  →role of AEs (unstable or externally launched) in burn control?

The essence of burning plasma physics is the coupling between different elements



– Full nonlinear coupling through effect of α's

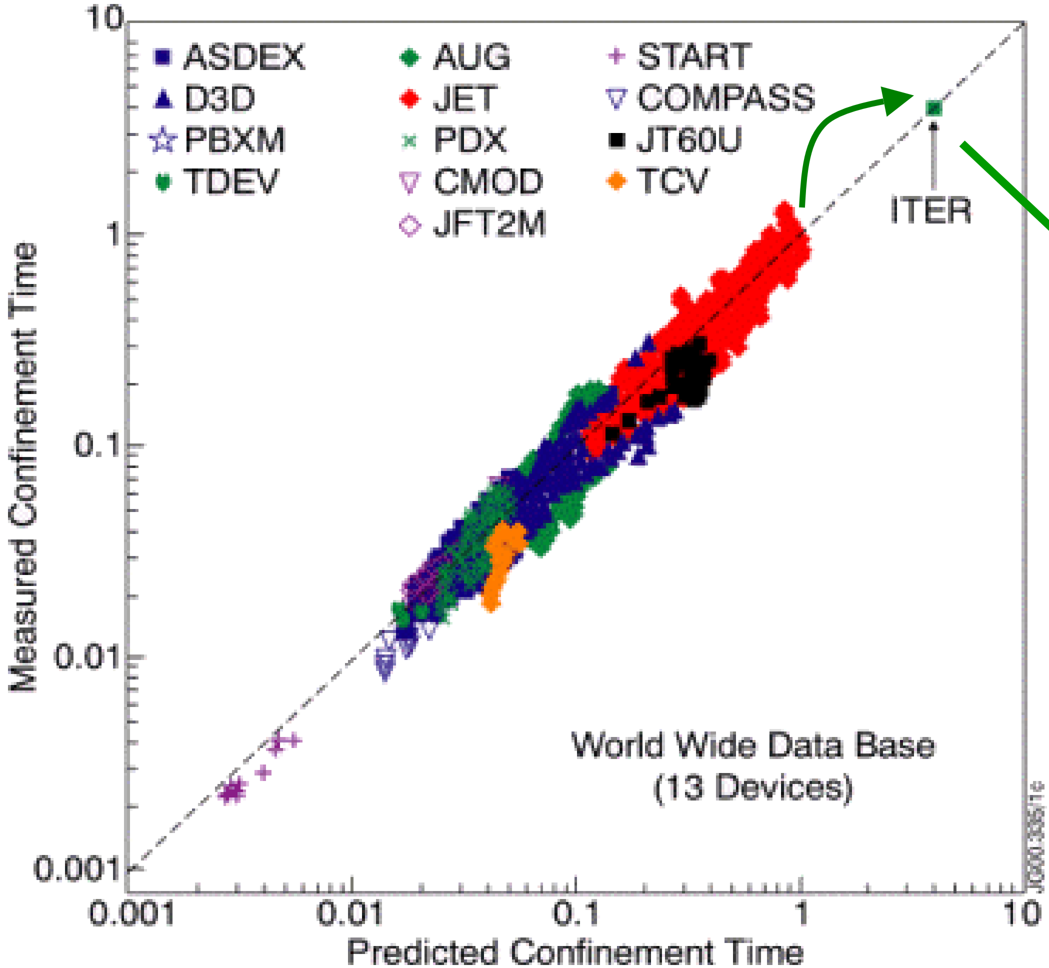
To understand burning plasmas we need a new device

Reaching the burning plasma regime

$Q \rightarrow 5\text{-}10$ for $n\tau_E \geq 10^{20}$ m^{-3}sec (T~10 keV): need $\tau_E \sim 5 - 10$s

- **Past and present expts.: empirical scaling of τ_E**

$$\tau_E \propto R^{1.97} B_T^{0.15} I_p^{0.93}$$



need large size, B_T, I_p

→ *ITER*

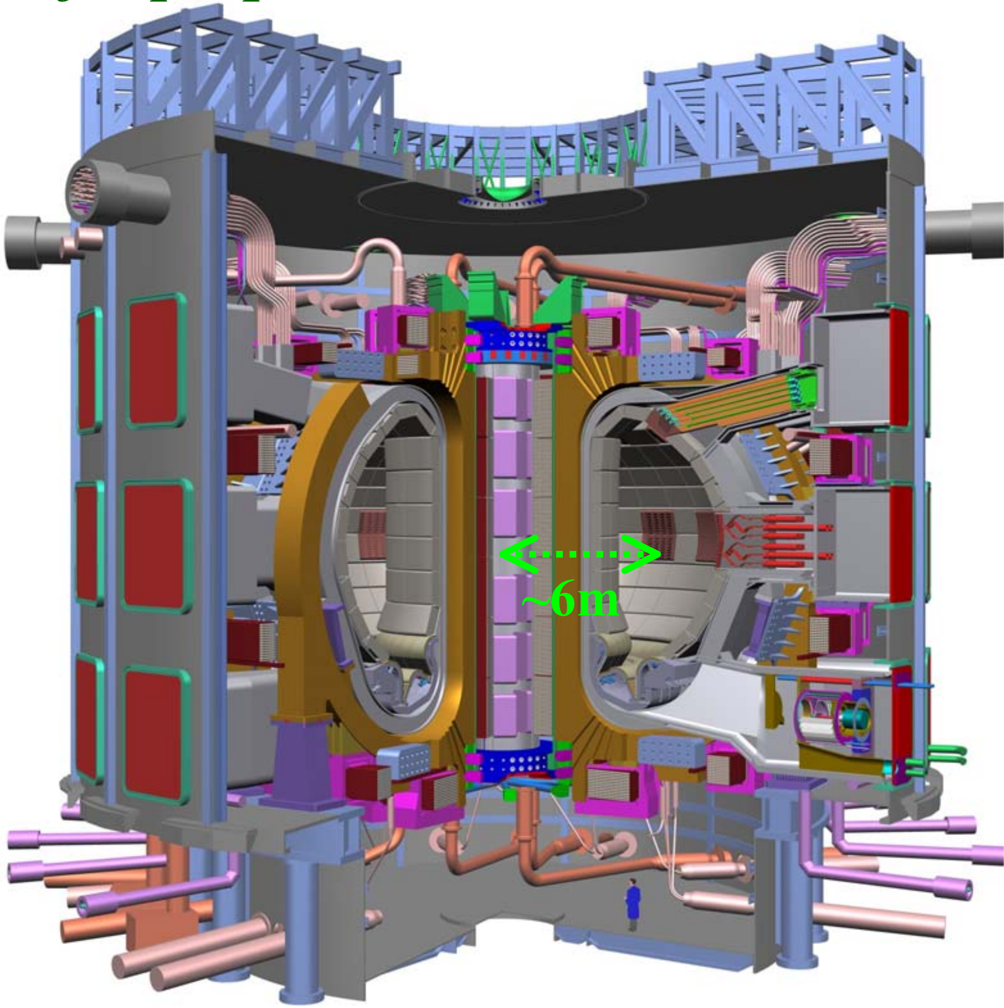
ITER: the world burning plasma experiment

Official goal: ***"To demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes."***

- ***Role of ITER***
  - **Burning plasma physics**

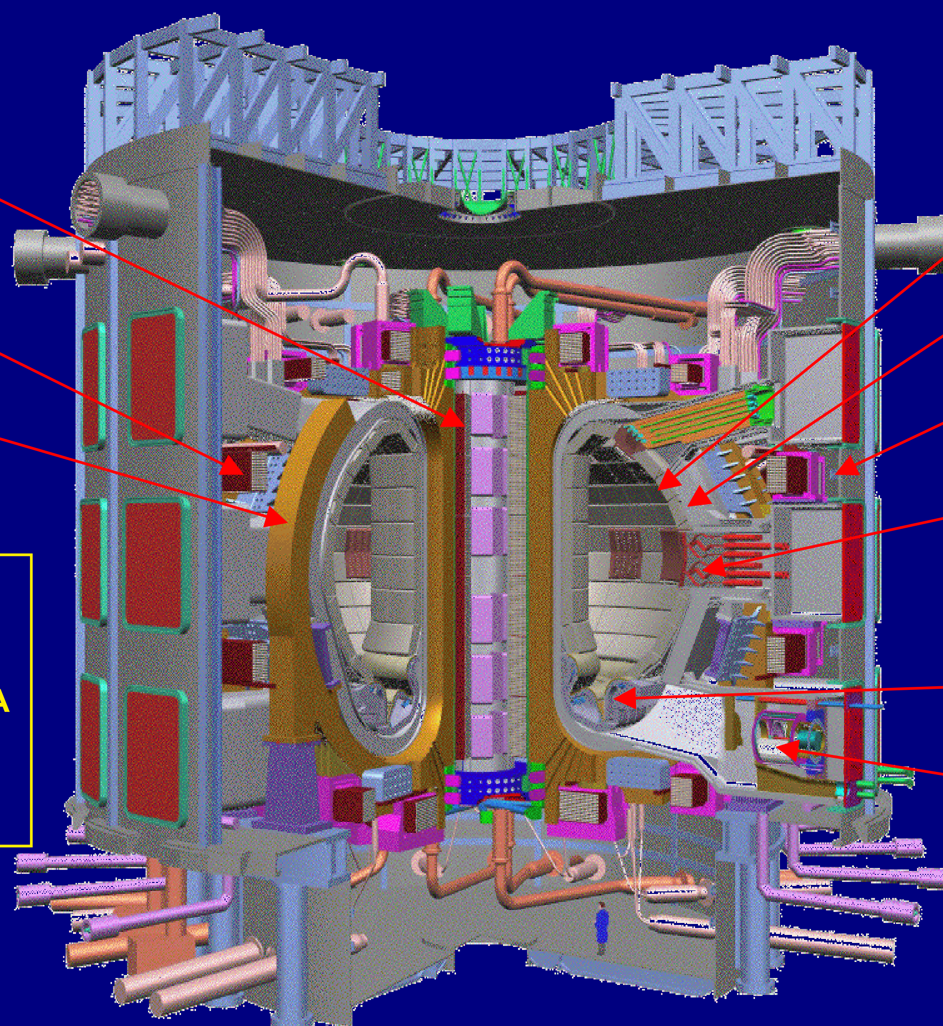
    P_{fusion}≥500MW for ~500s

    Q≥10, f_{α} ≥ 67%
  - ***Integration of physics and technology***
  - ***Demonstrate and test fusion power plant technologies and safety***



R~6.2m; B_T~5.3T; I_p~15MA

Design - Main Features



Central Solenoid
Nb_3Sn, 6 modules

Poloidal Field Coil
Nb-Ti, 6

Toroidal Field Coil
Nb_3Sn, 18

Blanket Module
440 modules

Vacuum Vessel
9 sectors

Cryostat
24 m high x 28 m dia.

Port Plug (IC Heating)
6 heating
3 test blankets
2 limiters/RH
rem. diagnostics

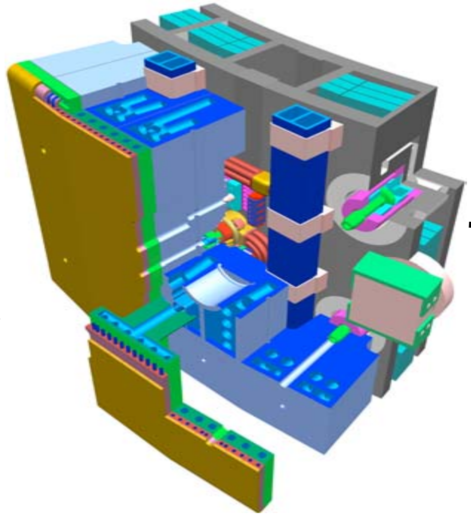
Divertor
54 cassettes

Torus Cryopump
8 units

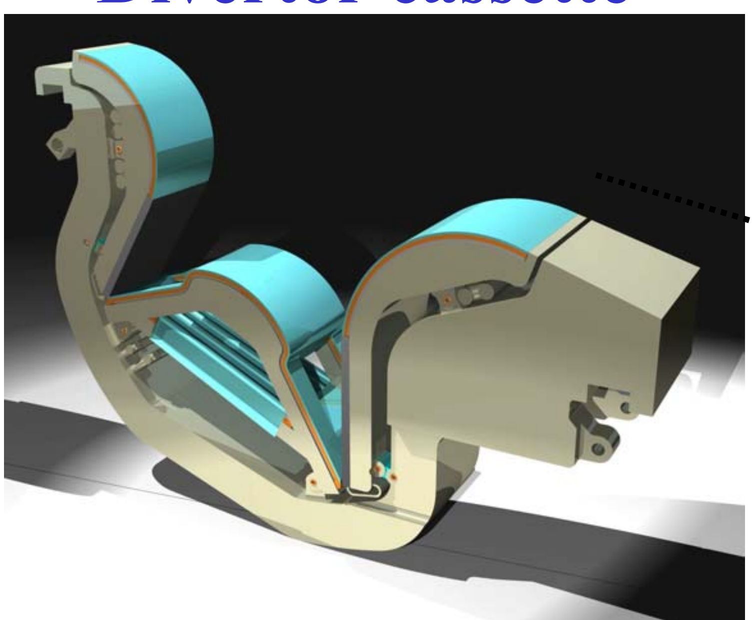
- Fusion Power: 500 MW
- Plasma Volume: 840 m^3
- Nominal Plasma Current: 15 MA
- Typical Temperature: 20 keV
- Typical Density: 10^{20} m^{-3}

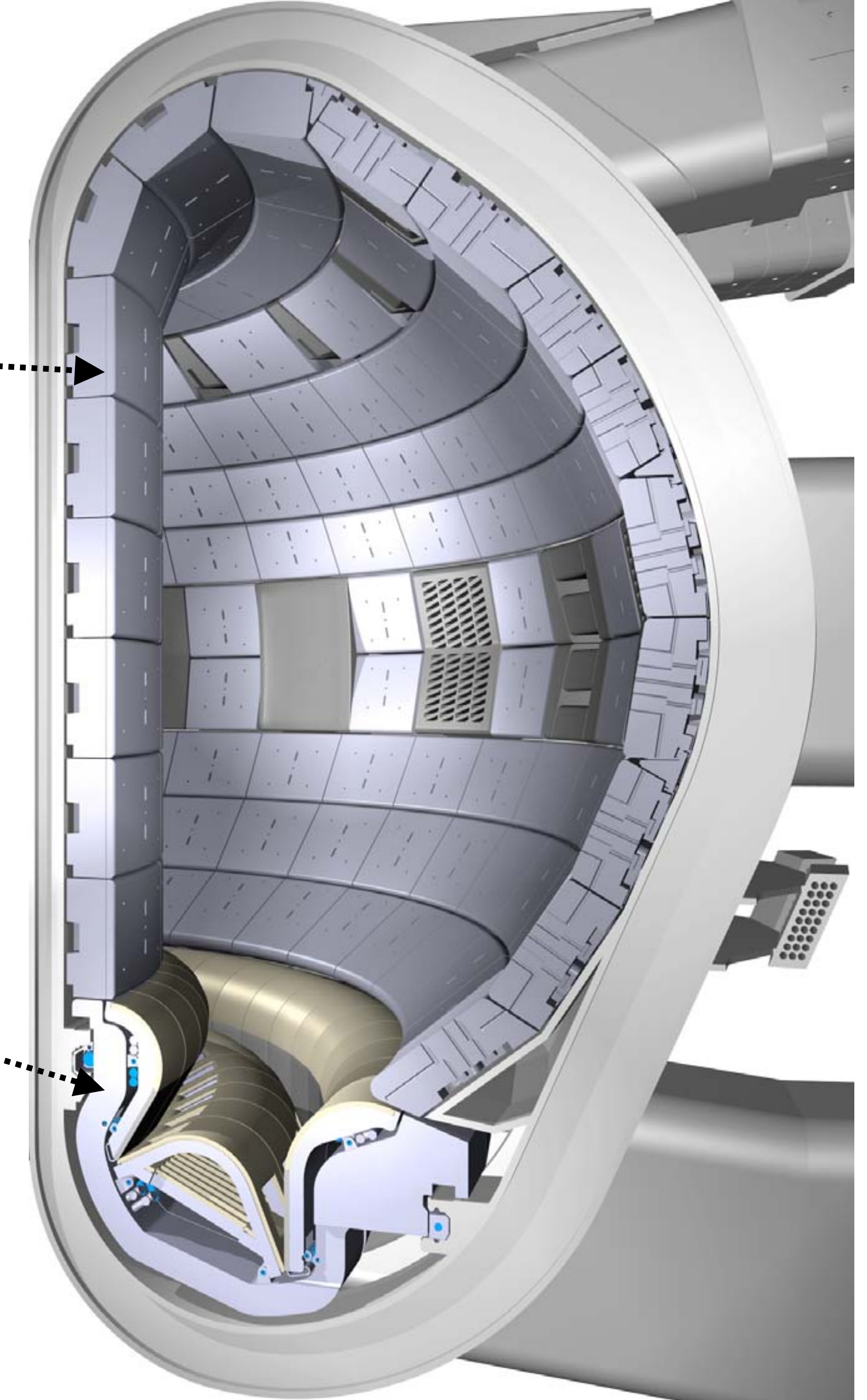
Cutaway of blanket module

Water cooled, combination of copper for thermal properties, steel for mechanical, and Be first surface

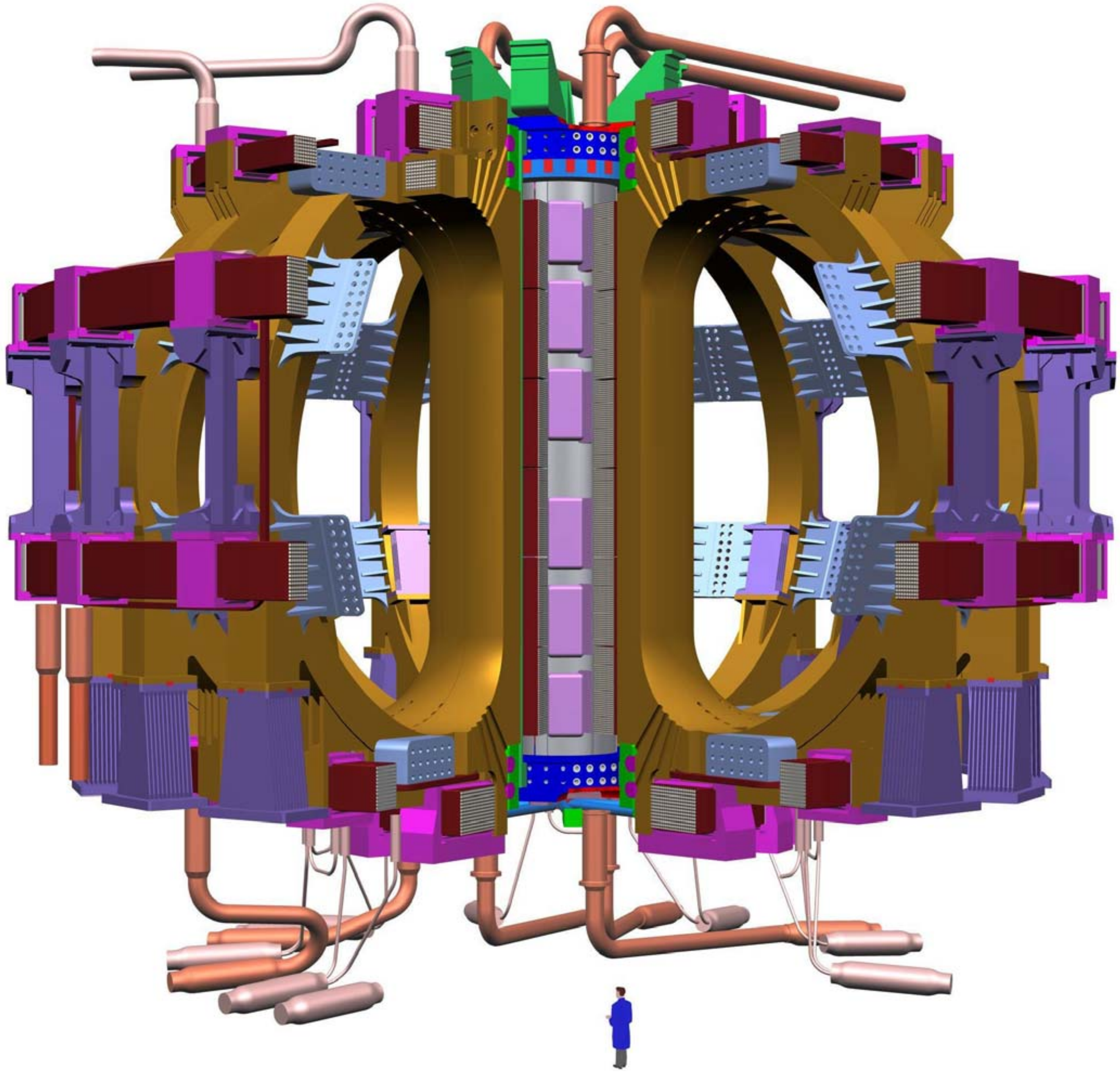


Divertor cassette

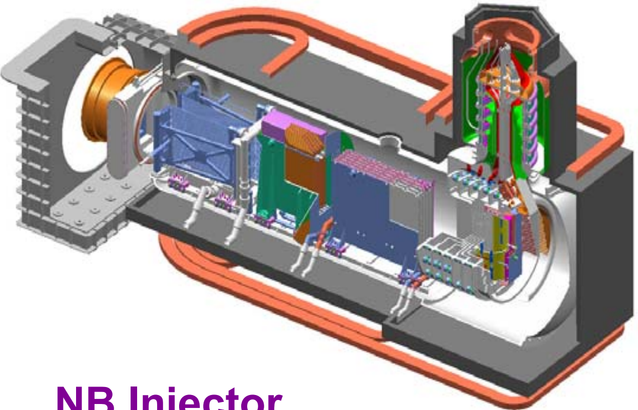




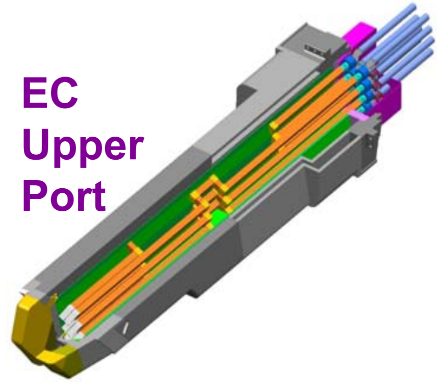
Magnet system with cryogenic coolant pipes



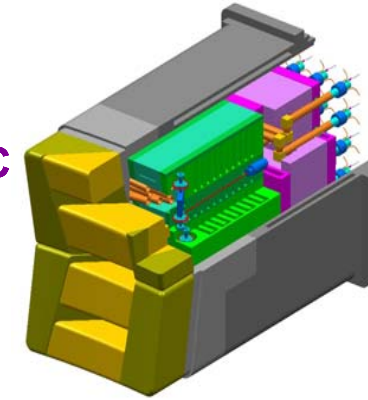
ITER Heating systems



NB Injector



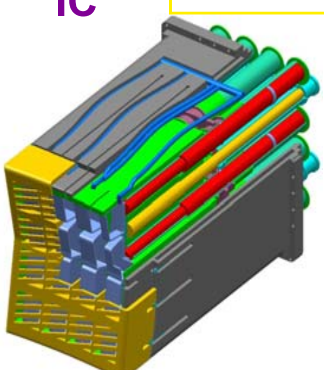
EC Upper Port

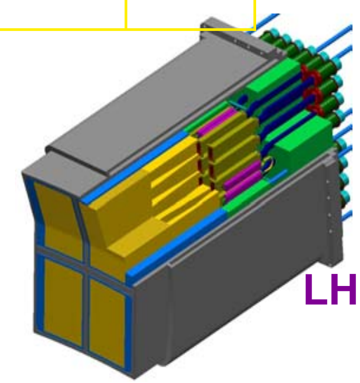


EC

	Startup		Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Power [MW]	**Equat. ports**	Power [MW]	Equat. ports	Power [MW]	Equat. ports	Power [MW]	Equat. ports	Power [MW]	Equat. ports
NB	**33**	**2**	33	2	50	3	50	3	50	3
IC	**20**	**1**	40	2	20	1	40	2	20	1
EC	**20**	**1**	40	1(1)	40	1(1)	40	1(1)	20	0(1)
LH	**0**	**0**	20	1	20	1	0	0	40	2
Total Installed	**73**	**4**	133	6	130	6	130	6	130	6

IC

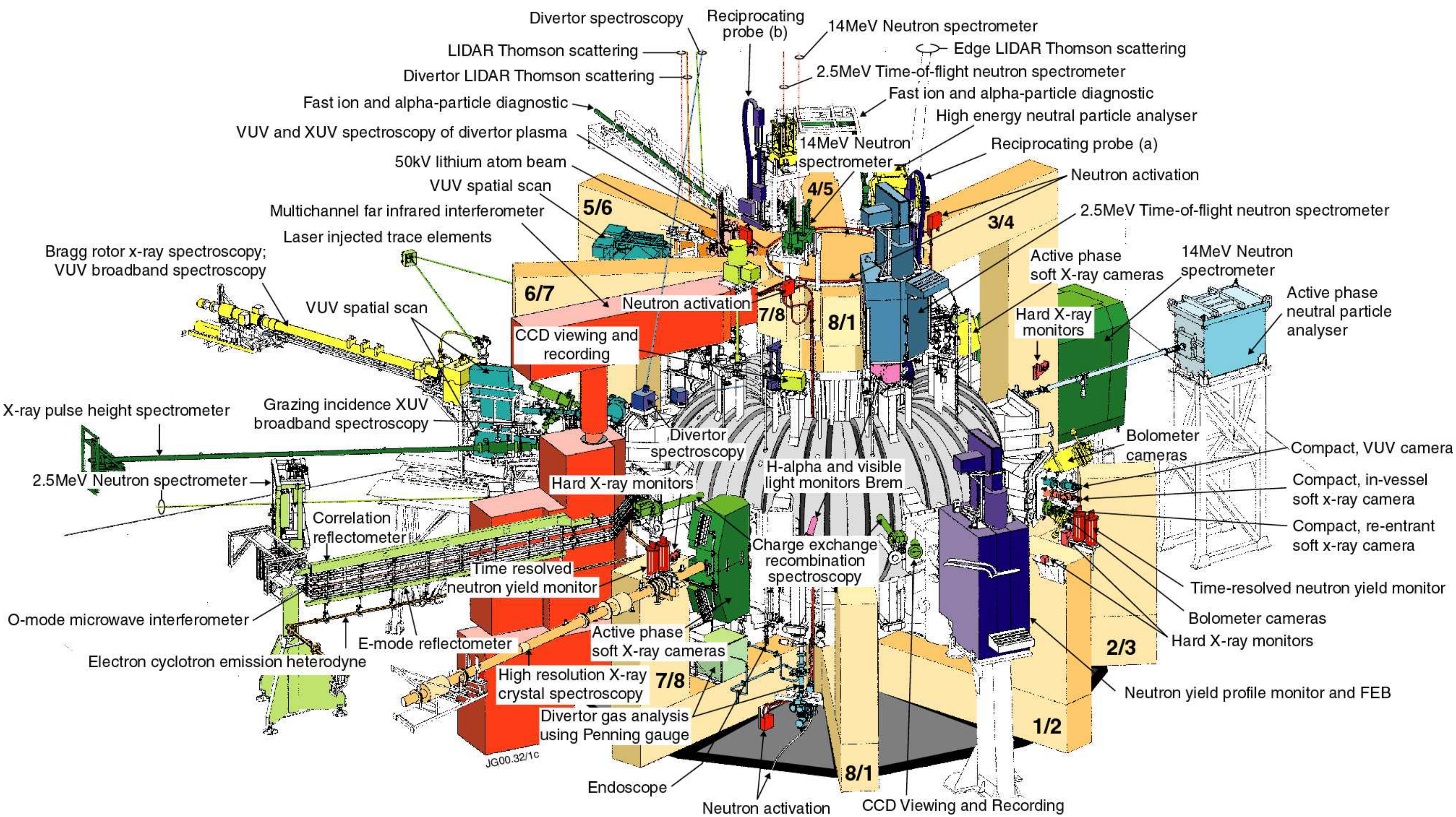




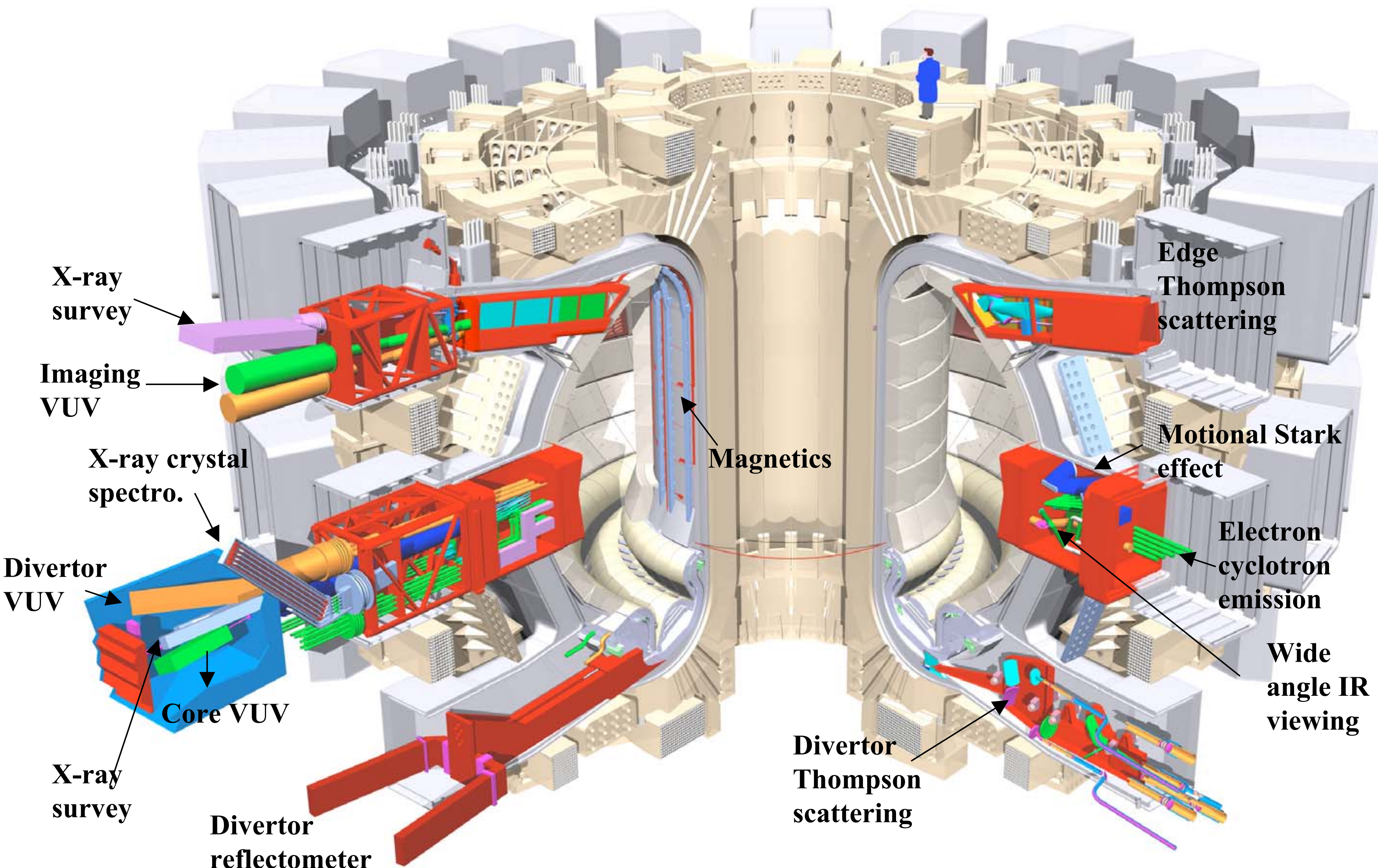
LH

EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET diagnostics

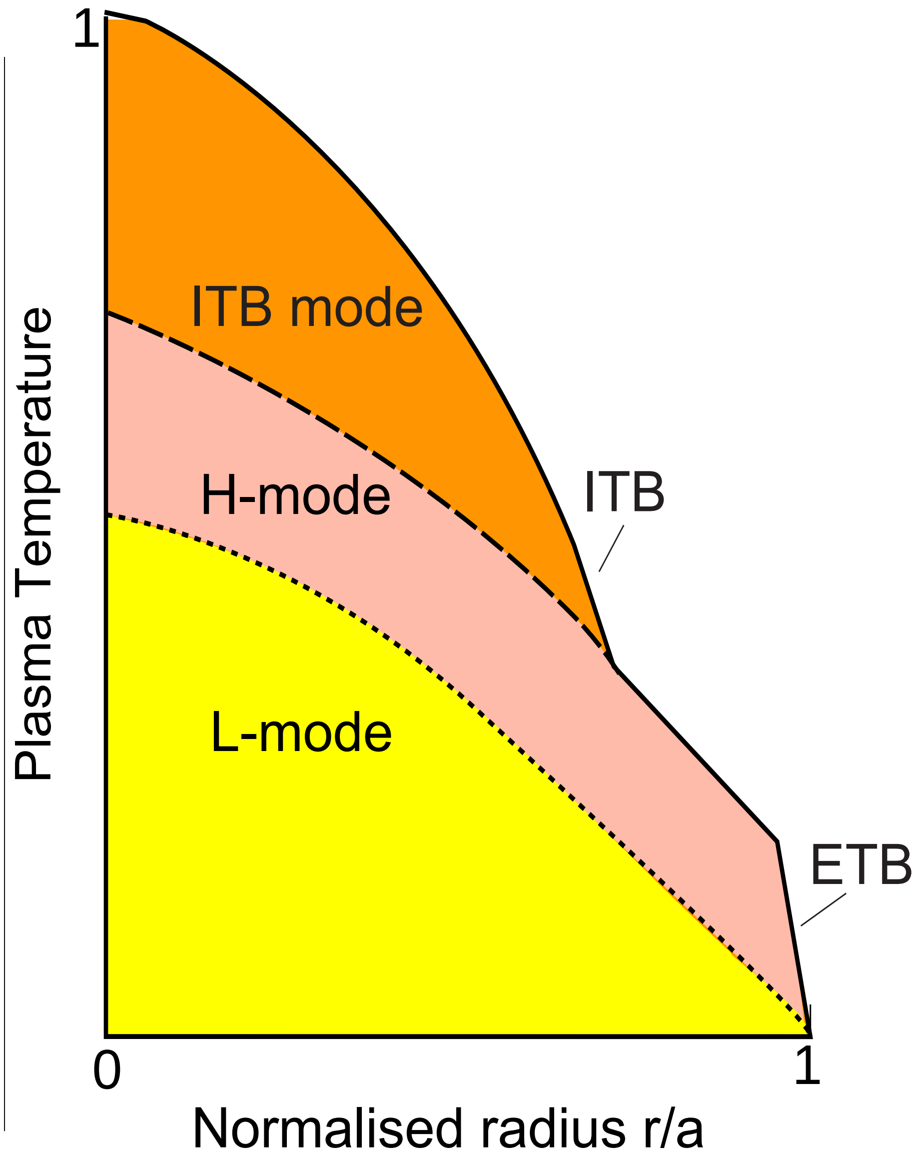


ITER diagnostics



ITER-Relevant Confinement Modes

- **H-mode (High Confinement Mode)**
  - Associated with formation of edge transport barrier
  - Reference mode for ITER inductive high-Q operation
- **Improved H-mode**
  - Candidate mode for inductive and/or hybrid ITER operation
- **Advanced Tokamak (AT) mode**
  - Associated with formation of Internal Transport Barrier (ITB)
  - Candidate mode for steady-state ITER operation

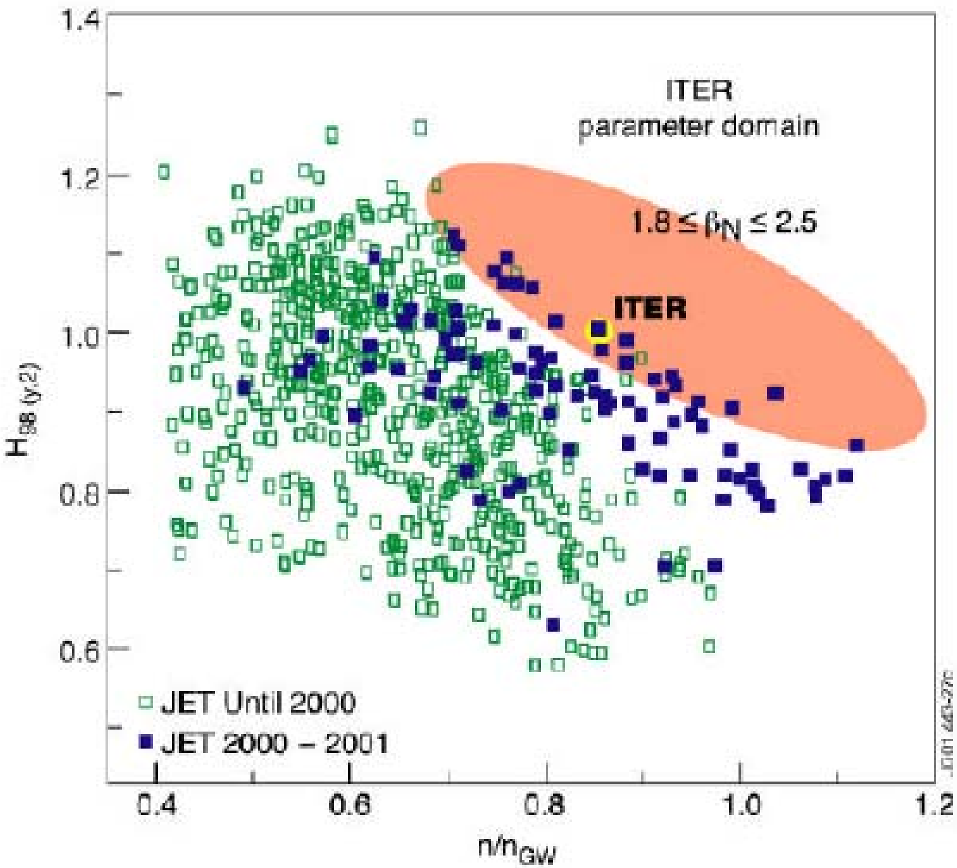


Physics Rules for Selection of ITER Design Parameters

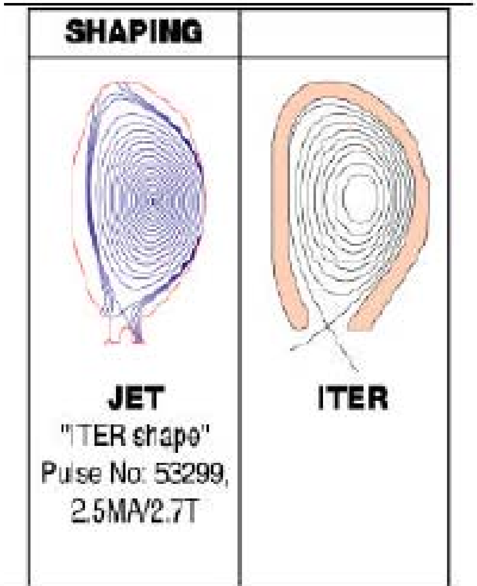
• $Q \geq 10$	$Q = 5P_\alpha/P_{aux}$
• ELMy H-mode	reference operation mode
• ITERH-98P(y,2) scaling	for energy confinement time
• Safety factor $q_{95} \geq 2.5$	$q_{95} \propto (5B/I)(\kappa a^2/R)$
• Electron density $n_e \leq n_G$	$n_G = I/(\pi a^2)$, empirical limit
• Normalized beta $\beta_N \leq 2.5$	$[\beta_N = \beta(\%)(aB/I)]$
• Strong plasma shaping	$\kappa_{sep} = 1.85$, $\delta_{sep} = 0.48$
• Heating power $P \geq 1.3\ P_{L\text{-}H}$	$P = P_\alpha + P_{aux} - P_{rad}$ $P_{L\text{-}H}$ is H-mode power thresh.

V. Mukhovatov et al., 30th EPS Conf. on Control. Fusion and Plasma Phys., July 7-11, 2003, St Petersburg, Russia

Q =10: ITER-simulation discharges on JET



JET-operating space

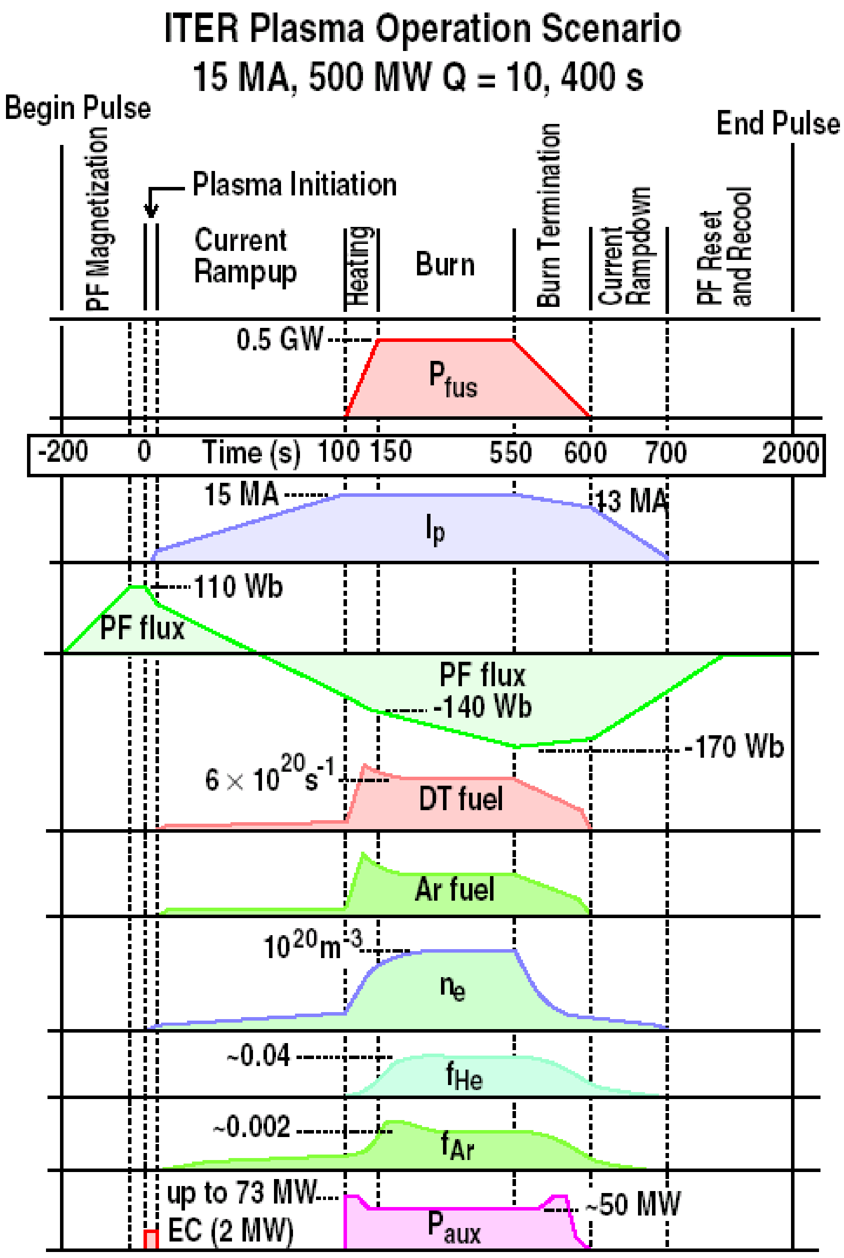


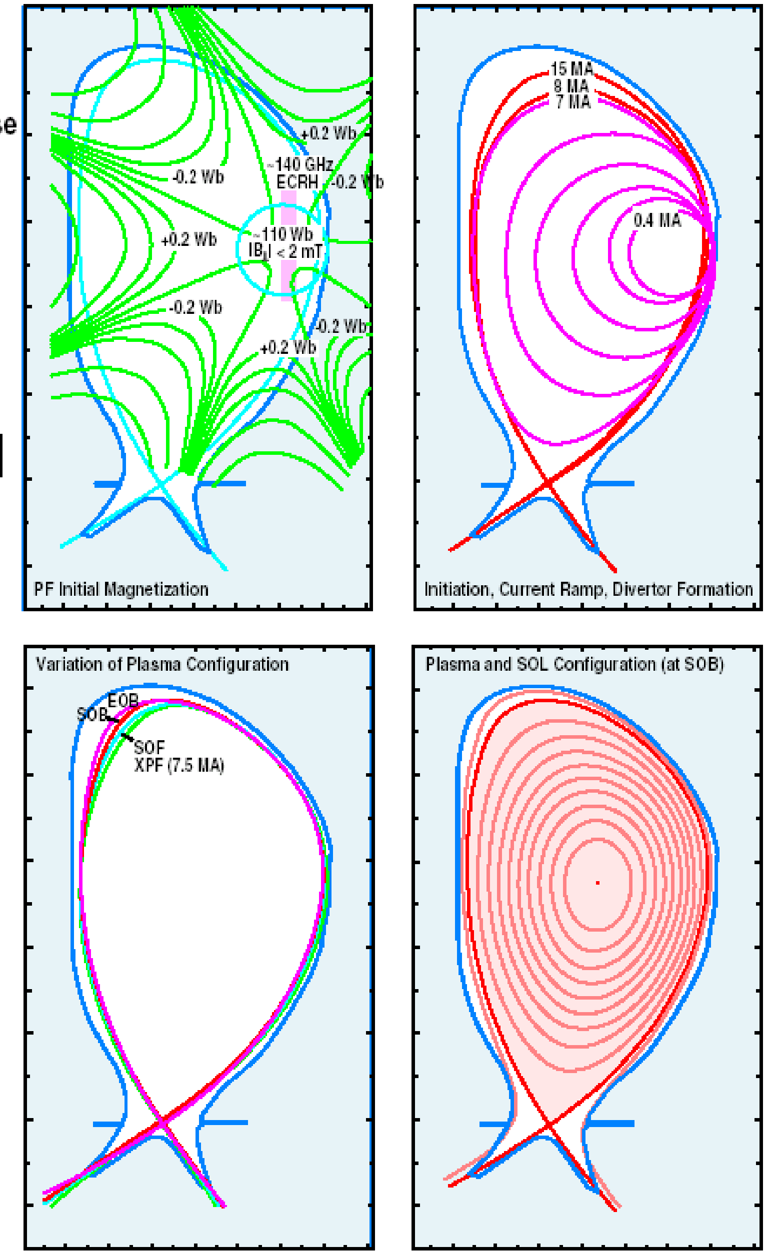
	JET	ITER
$H_{98(y,2)}$	0.91	**1.0**
$\beta_{N,th}$	1.90	**1.81**
n_e / n_{GW}	1.1	**0.85**
Z_{eff}	1.5	**1.7**
P_{rad} / P_{tot}	0.40	**0.58**
κ, δ	1.74, 0.48	**1.84, 0.5**
q_{95}	3.2	**3.0**
τ_{pulse} / τ_E	15	**110**

ITER Q=10 scenario main parameters

Parameter	Units	Value
Aspect ratio, A (= major radius/minor radius)	m/m	6.2 / 2.00
Volume, V	m^3	837
Surface	m^2	678
Cross-sectional area	m^2	21.9
On-axis toroidal field, B	T	5.3
Plasma current, I_p	MA	15.0
Elongation/triangularity - separatrix - 95% flux		1.86 / 0.5 1.75 / 0.35
Helicity safety factor at 95% flux surface, q_{95}		3.0
Normalised beta, β_N		1.77
Volume-averaged electron density, $<n_e>$	10^{19} m^{-3}	10.14
Factor relative to Greenwald, n/n_{GW}		0.85
Volume-averaged ion temperature, $<T_i>$	keV	8.1
Volume-averaged electron temperature, $<T_e>$	keV	8.9
Volume-averaged toroidal beta, $<\beta_T>$	%	2.5
Surface-averaged poloidal beta, β_p		0.67
α-particle power	MW	82
External heating power	MW	40
Radiated power	MW	48
Fusion power	MW	410
Margin on threshold power	MW/ MW	1.6
Energy multiplication, Q		10
Energy confinement time (scaling), τ_E	s	3.7
Required energy confinement time scaling enhancement factor, H_H		1.0
Effective atomic number, Z_{eff}		1.65

Ex. of ITER operating scenario





ITER as a physics experiment

- baseline („conventional“) scenarios: Elmy H-mode Q = 10 and „hybrid“ scenario

single confinement barrier

physics: extrapolation of well understood regime to/in

- self heating
- physics of α-particles
- divertor & PSI

– identifiable milestone
– technology - physics integration
– technology test & demonstration

- advanced scenarios:

multiple confinement barriers

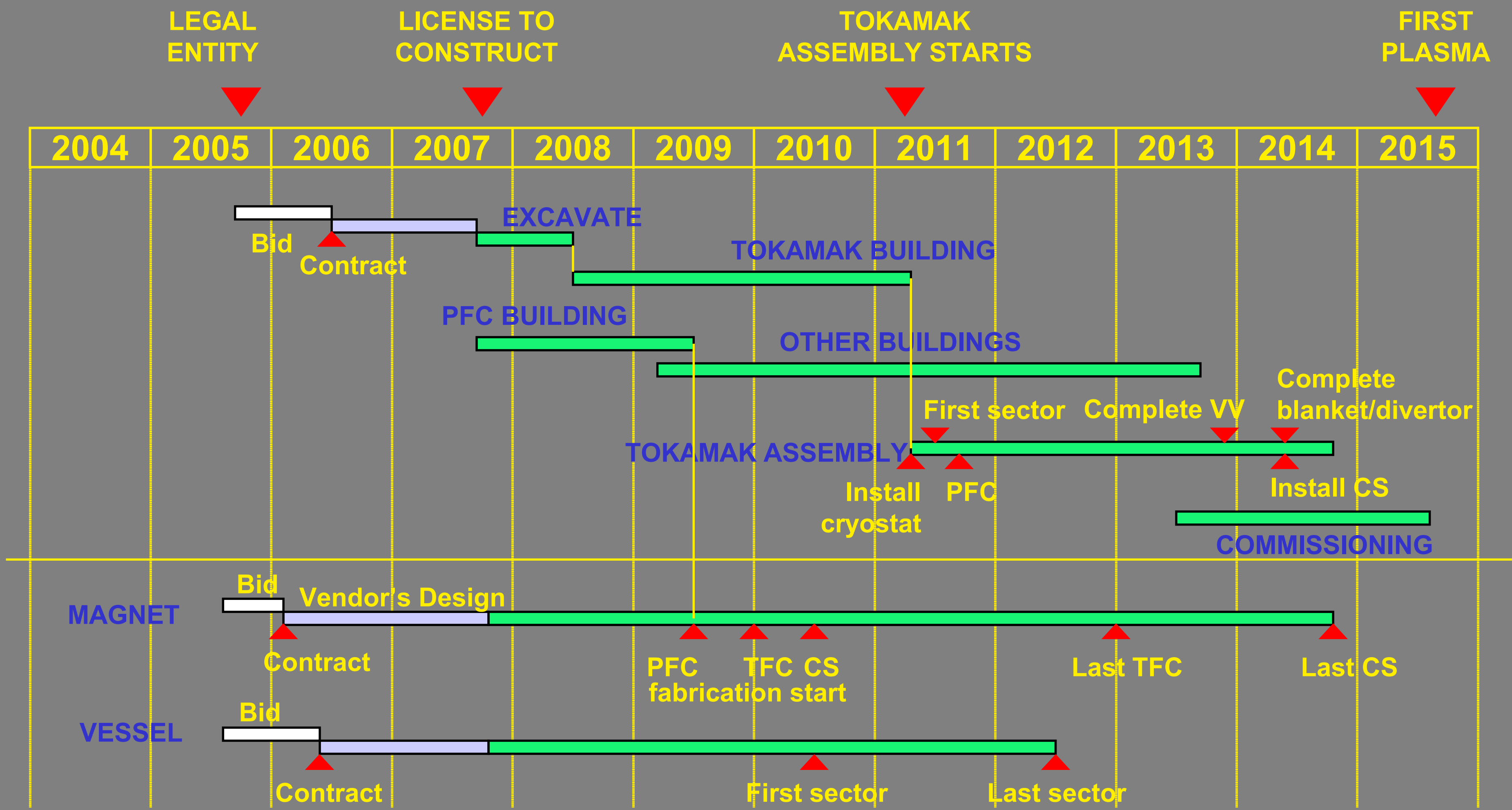
develop physics: (a range of scenarios exist)

- extrapolation of regime
- self-consistency of equilibria
- MHD stability
- compatibility with divertor requirements and impurity concentrations
- compatibility with satisfactory α-confinement
- controllability

– satisfy steady state objective
– prepare DEMO

K.Lackner, EFDA

Construction Schedule



Negotiations

- Began in July 2001 with the following aims

  draft Joint Implementation Agreement

  select ITER construction site

  agree how the procurement and costs will be shared

  define how the project will be managed and identify the DG and senior staff

- Provisional agreement on all the above achieved by Dec. 2003

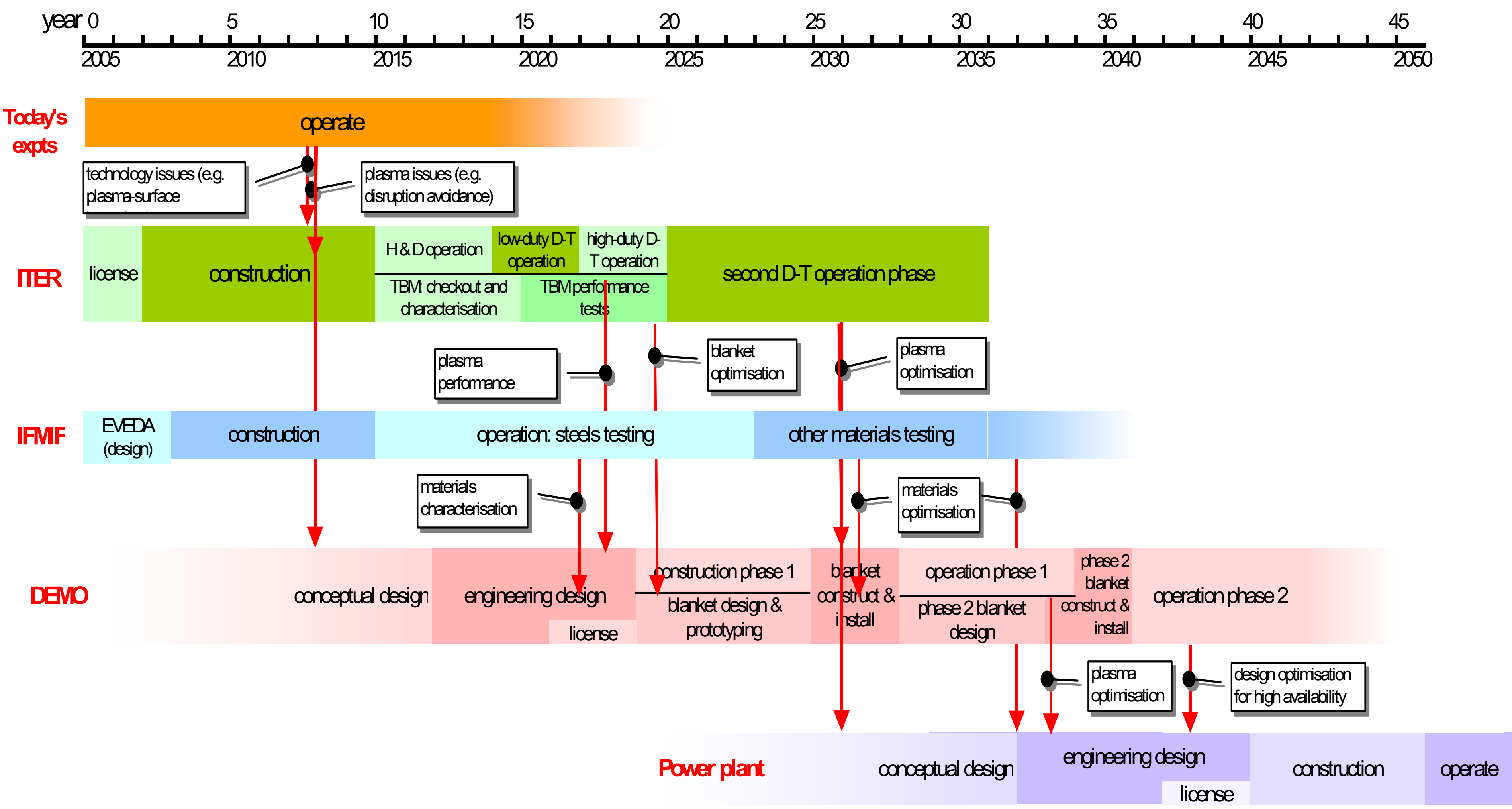
- Deadlocked over choice of construction site.

A *fast track* for fusion?

1. **On same time scale**
   - **ITER: physics and technology of a burning plasma**
   - **IFMIF: material tests**
2. **DEMO - assumed ITER-like**
   - **Final integration and reliability development. Several DEMOs in parallel?**
3. **Commercial power**

From Chris Llewellyn Smith, Director of UKAEA Culham

PRELIMINARY



From Chris Llewellyn Smith, Director of UKAEA Culham

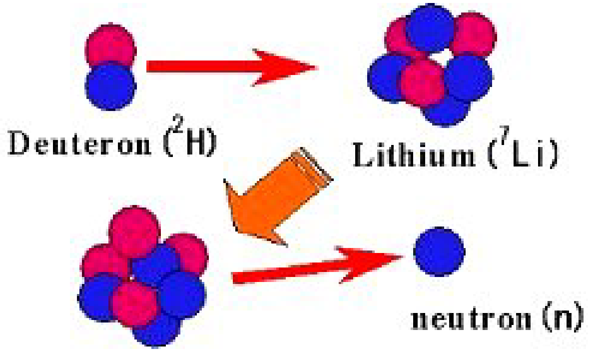
Construction Cost Sharing

Party	Share	Total
CN-KO-RF-US	10% each	40%
JA + EU	Host: 36%+A Non-Host: 10%+B (A+B=14%)	60%

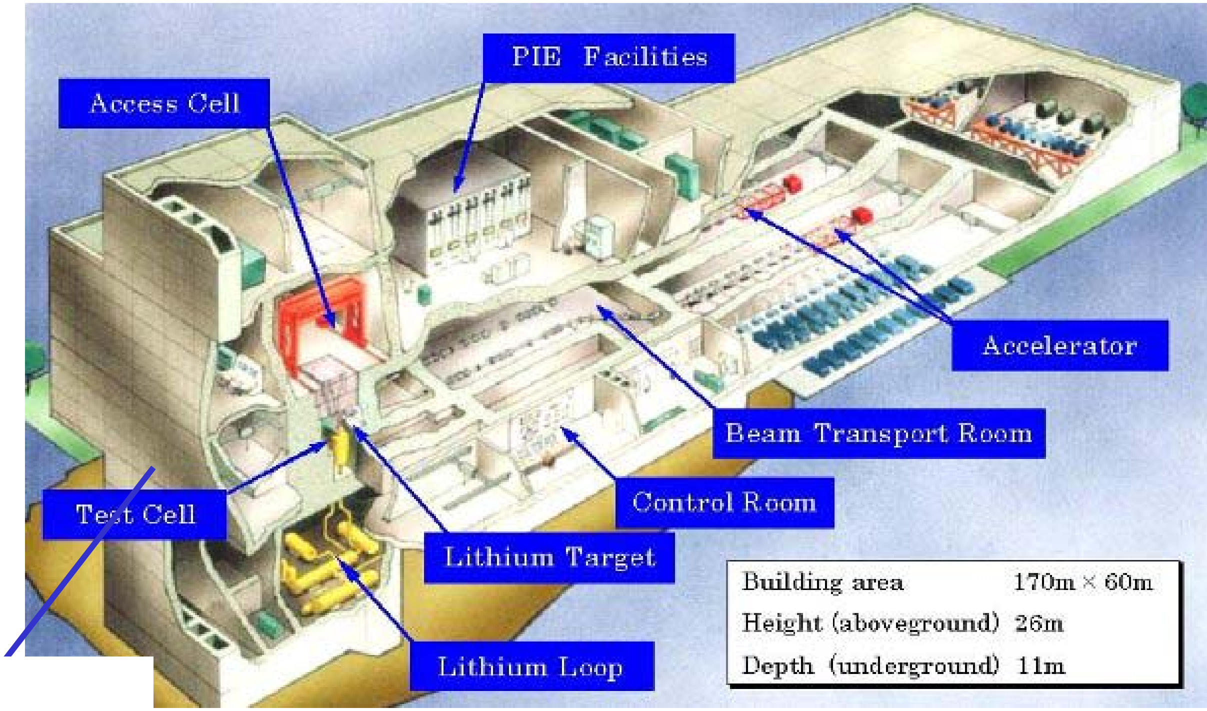
- Host provides Buildings and Utilities. Remaining allocation (A+B) depends on site and final agreement.

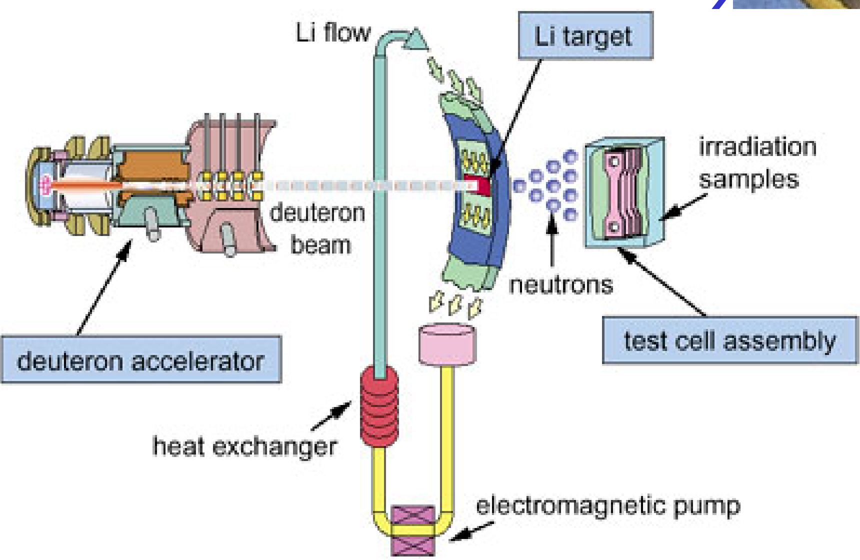
- CN: magnet supports,feeders, correction coils, conductors, blanket (0.2), cryostat, gas injection, casks (0.5), HV substation, AC/DC (0.35), diag.
- EU: TF(0.5), conductors, cassette and outer target, vac.pumps, div. RH, casks (0.5), isotope sep., IC, EC, diag.
- JA: TF(0.5), conductors, inner target, blanket RH, EC, diag.
- KO: conductors, vessel ports (0.67), blanket (0.2), assembly tools, thermal shield, T storage, AC/DC (0.65), diag.
- RF: PF1, conductors, vessel ports (0.33), blanket (0.2), port limiters, flexibles, dome and PFC tests, Discharge circuits, EC, diag.
- US: CS(0.5), conductors, blanket (0.1), vac.pumps, pellet inj., vessel/in-vessel cooling, tok exh. proc., IC, EC, diag.

IFMIF



100 D produce ~7 n with E ≤55MeV





Requirements:

volume ~ 0.5 l

neutron flux ~ 2 MW/m^2 (9×10^{13} n/cm^2 s)

Such flux would give ~20dpa on fusion reactor first wall

Total irradiation yield 100-200 dpa