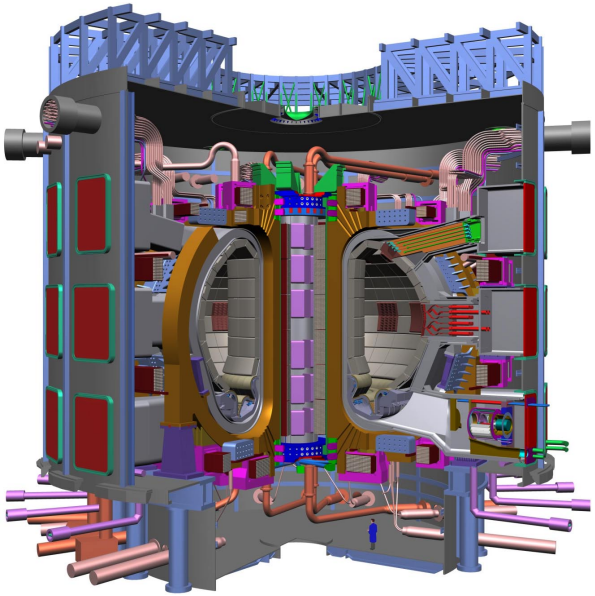

ITER
A Burning Plasma Experiment

prepared by D J Campbell and K Lackner

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Acknowledgements

Many members of the ITER International Team and ITER Participant Teams

Synopsis

- **The ITER Design**
- **ITER's Aims and Role**

- **Baseline scenarios:**
  - ELMy H-mode Q=10
  - Hybrid

Single confinement barrier

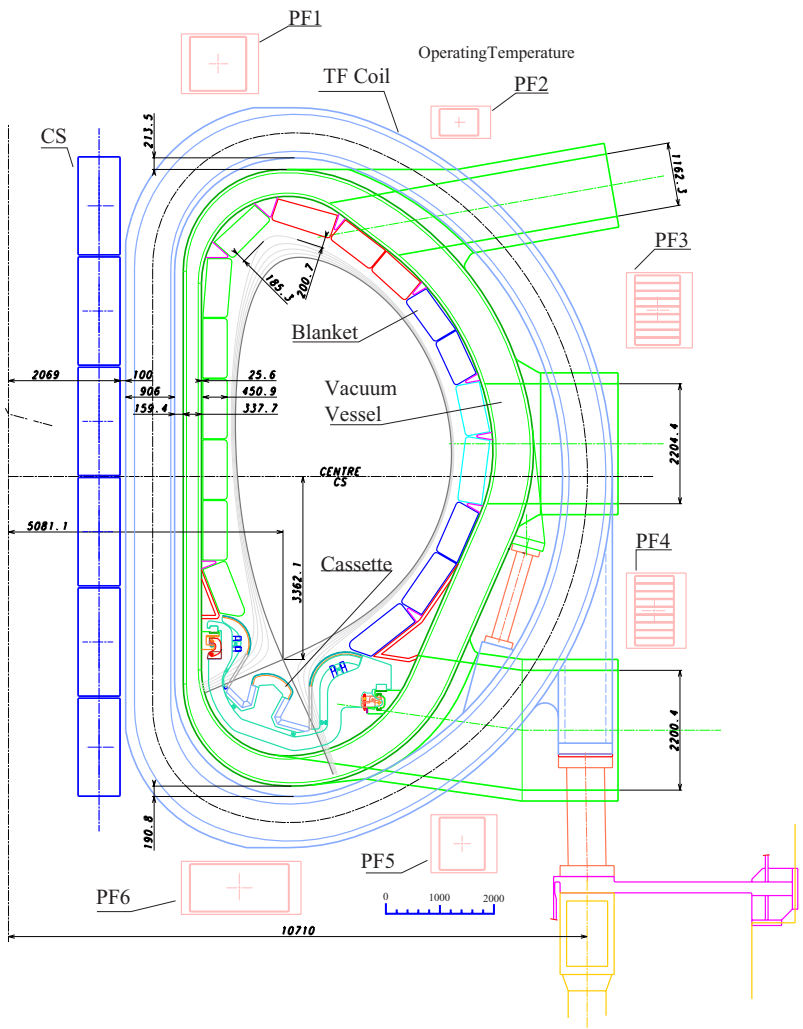
  - identifiable milestone
  - well understood physics extrapolation to:
    - self-heating
    - α-particle physics
    - divertor/ PSI issues
  - physics-technology integration
  - technology test & demonstration

- **Advanced scenarios:**

Multiple confinement barriers

  - satisfy steady-state objective
  - prepare DEMO
  - develop physics in a range of scenarios:
    - extrapolation of regime
    - self-consistent equilibria
    - MHD stability
    - divertor/ impurity compatibility
    - satisfactory α-particle confinement
    - controllability

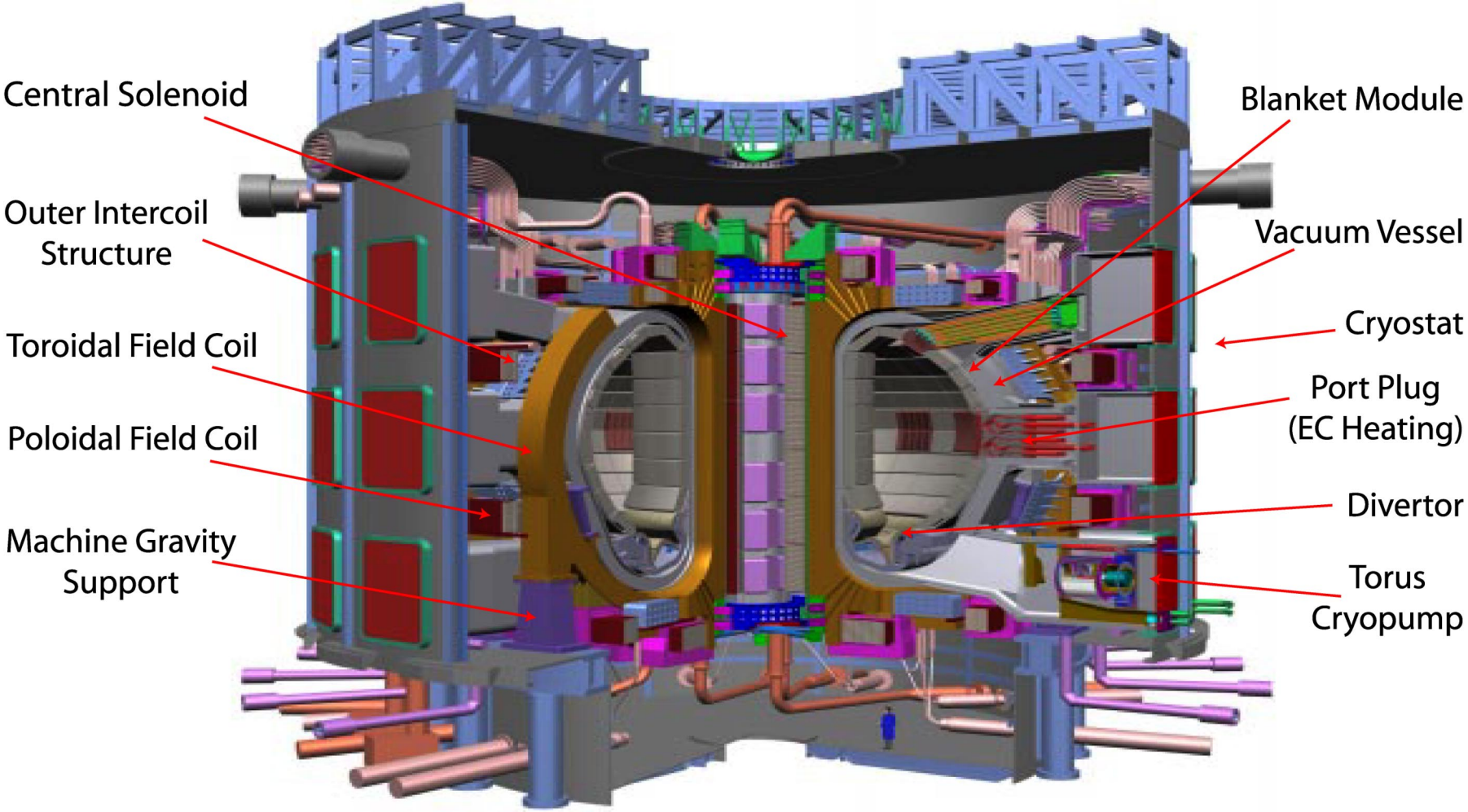
The ITER Design: Poloidal Elevation



	ITER
Major radius	6.2 m
Minor radius	2.0 m
Plasma current	15 MA
Toroidal magnetic field	5.3T
Elongation / triangularity	1.85 / 0.49
Fusion power amplification	≥ 10
Fusion power	~400 MW
Plasma burn duration	~400 s

ITER parameters in Q = 10 reference inductive scenario

ITER Main Design Features



ITER Design Goals

Physics:

- ITER is designed to produce a plasma dominated by α-particle heating
- produce a significant fusion power amplification factor ($Q \geq 10$) in long-pulse operation
- aim to achieve steady-state operation of a tokamak ($Q = 5$)
- retain the possibility of exploring 'controlled ignition' ($Q \geq 30$)

Technology:

- demonstrate integrated operation of technologies for a fusion power plant
- test components required for a fusion power plant
- test concepts for a tritium breeding module

ITER Standard Inductive Scenario

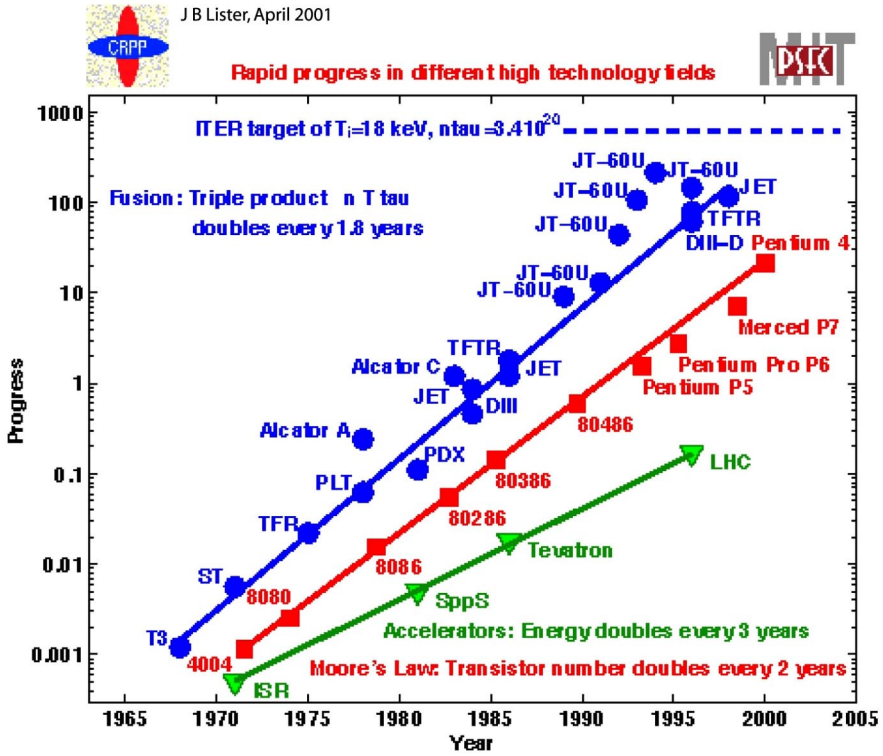
1 Demonstrate milestone
- shows identifiable progress to public and politics
- also required to support development of alternatives

2 Verify and extend scalings and theoretical models
- Confinement, H-mode access, ELMs, NTMs …..

3 Qualify α-particle heating as plasma heating technique

4 Test of plasma-wall interactions at high power & long pulse
- match wall equilibration time
- tritium inventory control

Maintain momentum



ITER Standard Inductive Scenario

Physics Design Rules

1 Confinement:

- τ_E scaling: IPB98(y,2)
- ITER H-mode threshold scaling

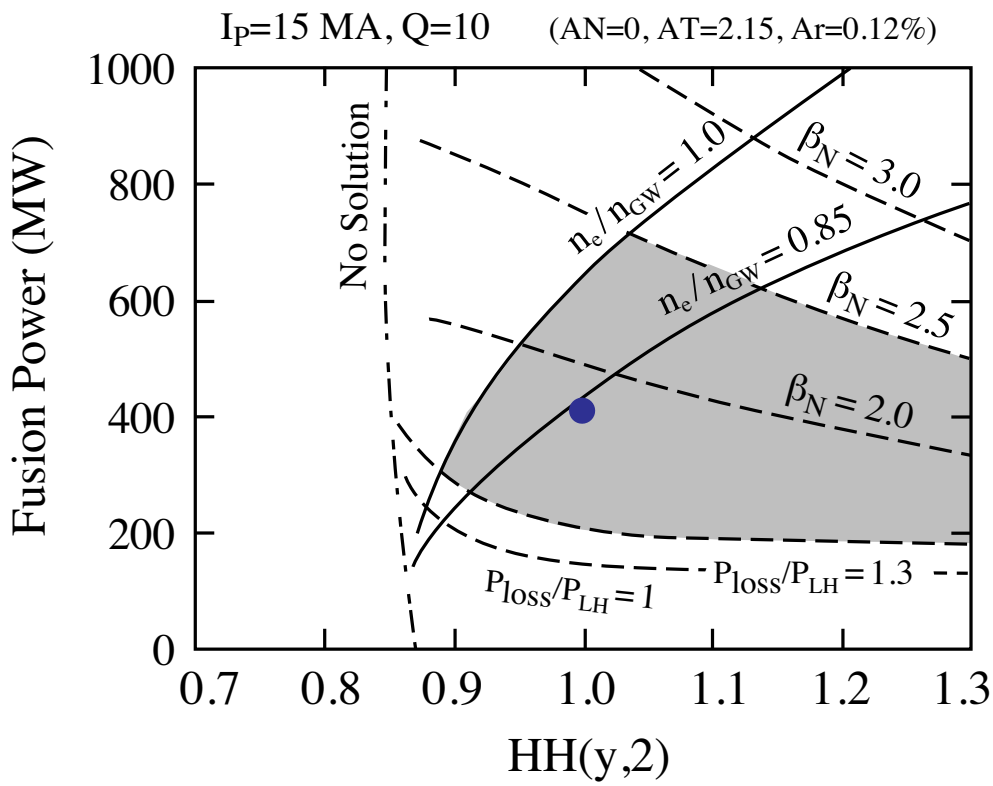
2 MHD stability:

- $q_{95} = 3$
- κ, δ determined by control requirements
- $n \leq n_{GW}$
- $\beta_N \leq 2.5$

3 Divertor:

- Peak target power ≤ $10 MWm^{-2}$
- $\tau_{He}^*/\tau_E \sim 5$
- $n_{Be}/n_e = 0.02$

Q=10 at 15MA (q_{95}=3)

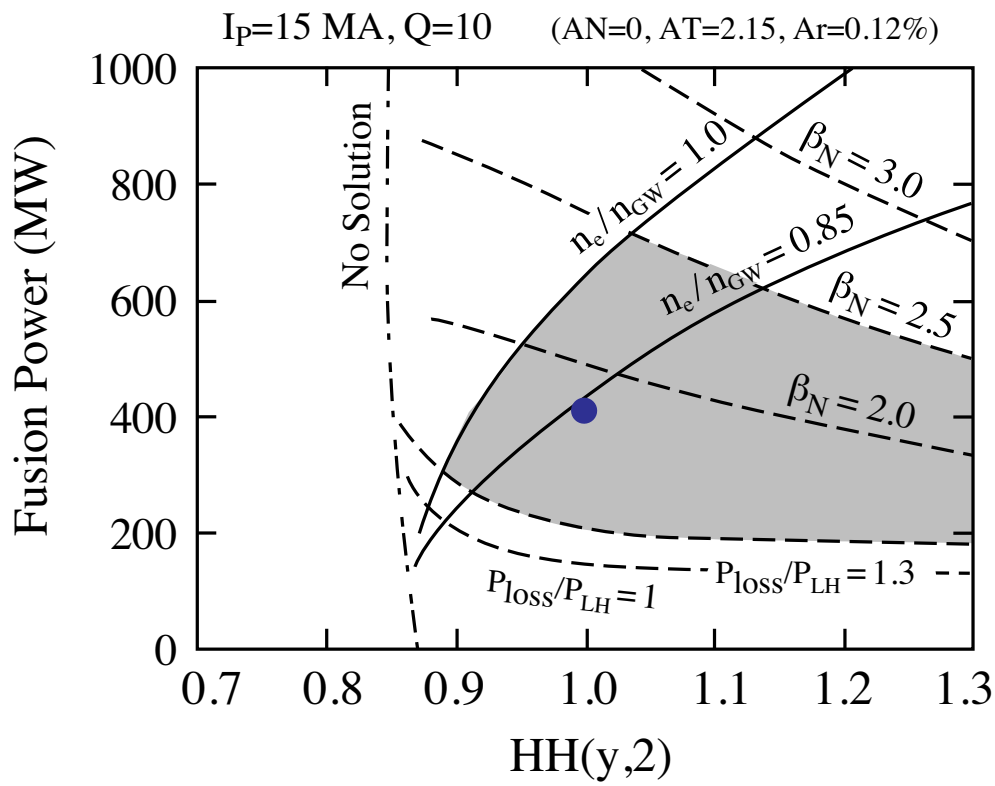


ITER Standard Inductive Scenario

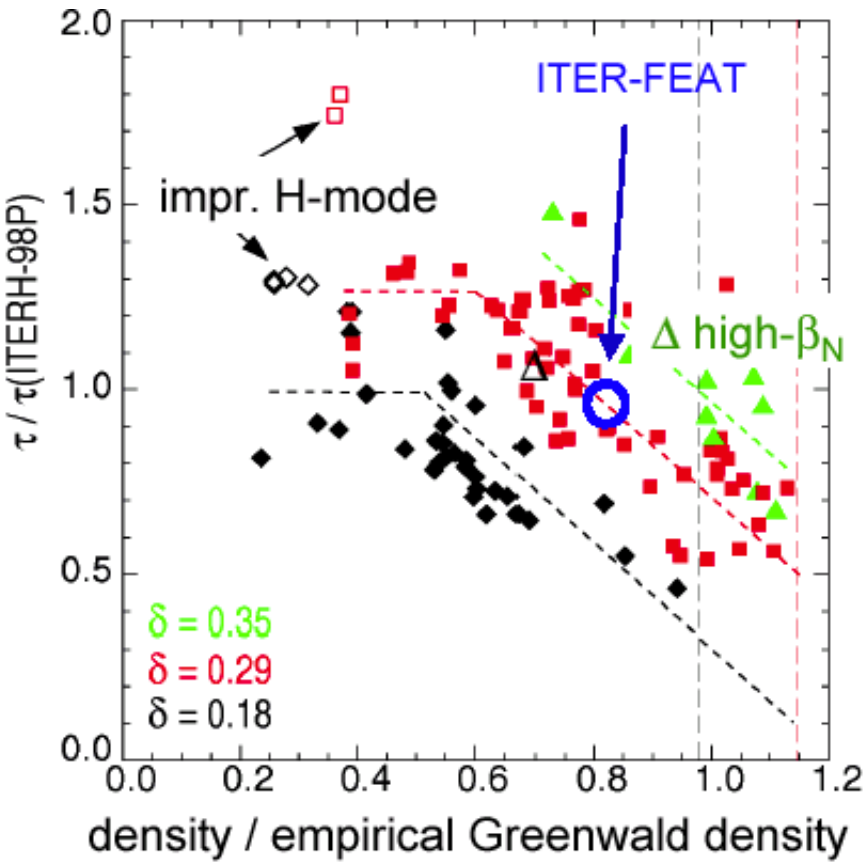
Conservative requirements

Parameter	400 MW	500 MW
B_T (T)	5.3	5.3
I_P (MA)	15.0	15.0
κ_X / δ_X	1.85 / 0.48	1.85 / 0.48
q_{95}	3	3
$\langle n_e \rangle$ (10^{19} m^{-3})	10.1	11.3
→ n_e/n_G	0.85	0.94
$\langle T_e \rangle$ (keV)	9.1	9.1
$\langle T_i \rangle$ (keV)	8.0	8.1
→ β_N	1.82	2.0
$\langle \beta_T \rangle$ (%)	2.6	2.8
τ_E, s	3.7	3.4
W_{th}, (MJ)	326	357
W_{fast}, (MJ)	31	33
→ $H_{H\text{-}IPB\ 98\ (y,2)}$	1.0	1.0
τ_α^* / τ_E	5.0	4.9
$f_{He,axis}$ (%)	4.3	4.3
$f_{Be,axis}$ (%)	2.0	2.0
Z_{eff}	1.66	1.81

Q=10 at 15MA (q_{95}=3)



Q=10 Issues: Confinement

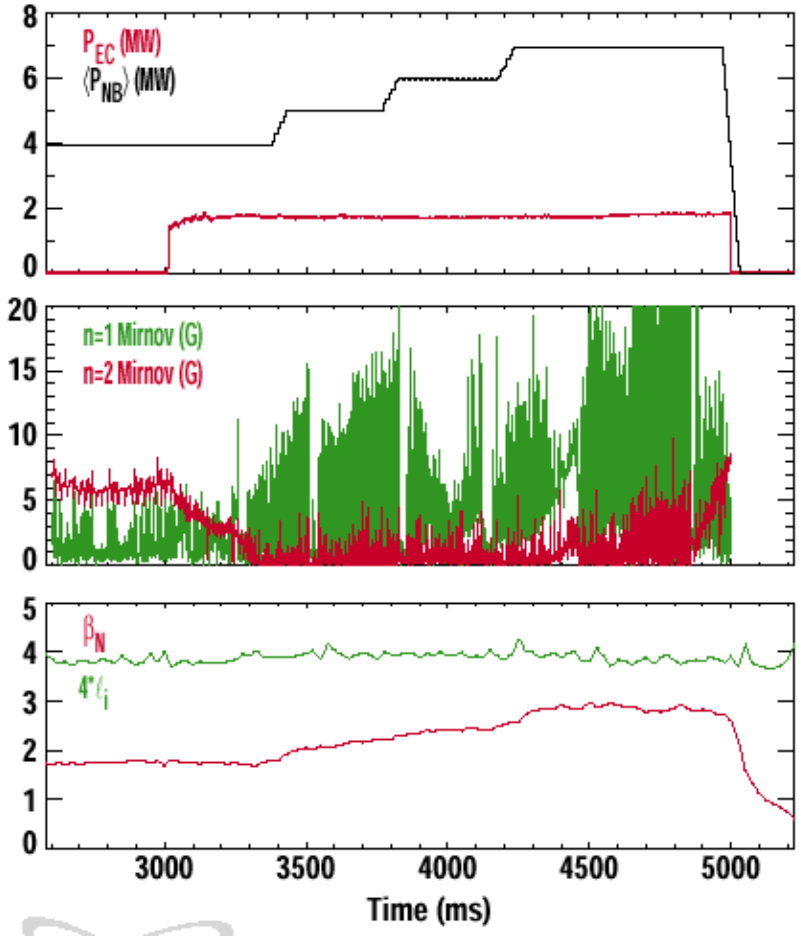


ASDEX-U

- H-factor at $n/n_{GW} > 0.85$ was previously a concern
- Experiments in several devices have shown benefit of high shaping
  - Extensive database of high density, high confinement data now available

Q=10 Issues: NTMs

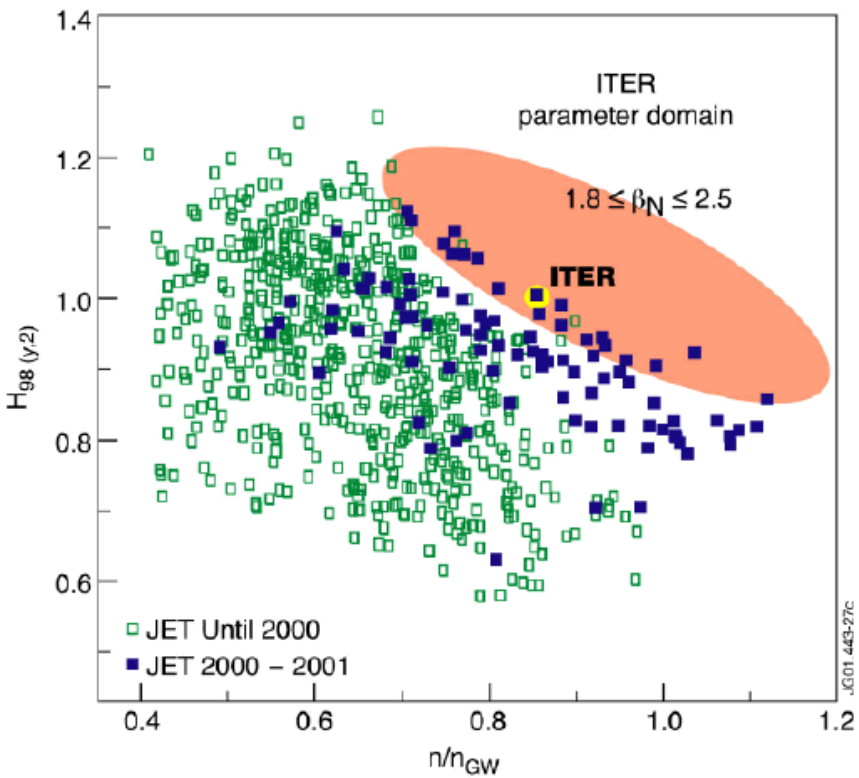
- NTMs can determine the β-limit below ideal limit
- Several successful approaches developed which allow expansion of inductive operating regime:
  1 Active ECCD feedback stabilization
  2 Sawtooth control of seed island trigger by ICCD / ECCD
  3 self-limitation via FIR NTMs (AUG & JET)

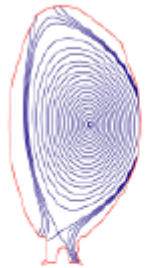
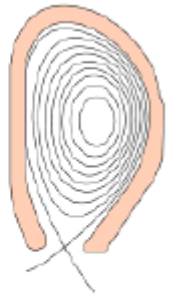


DIII-D

Q=10 Issues: Sustained Performance

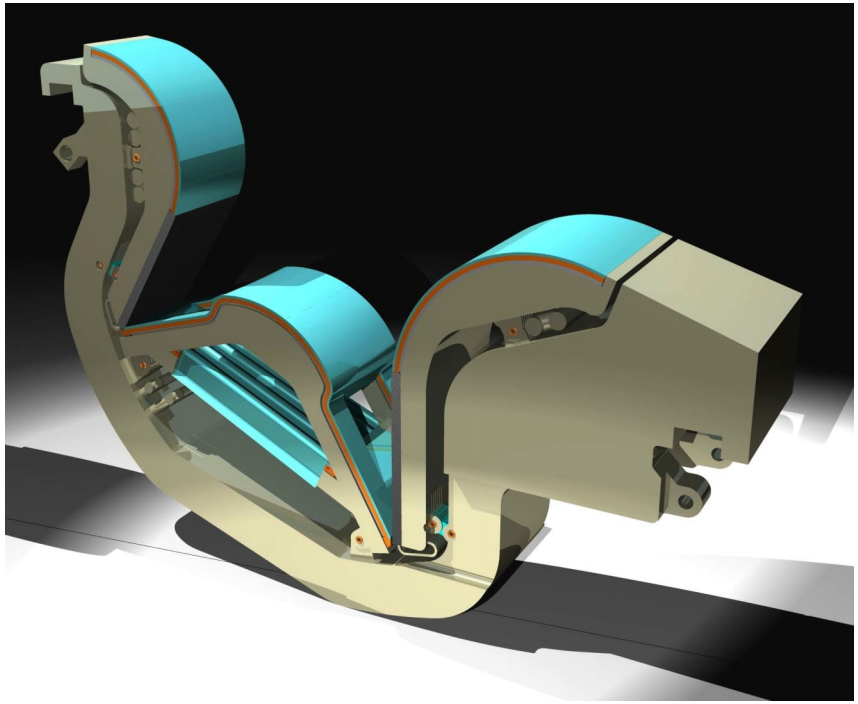
ITER-simulation discharges on JET

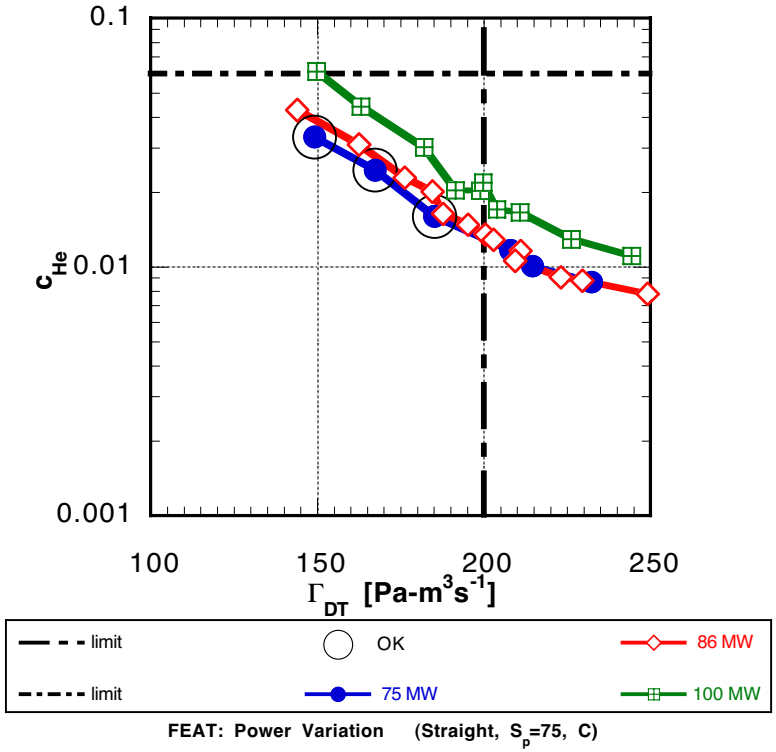


SHAPING		
		
	JET "ITER shape" Pulse No: 53299, 2.5MA/2.7T	**ITER**
$H_{98\,(y,2)}$	0.91	**1.0**
$\beta_{N,th}$	1.90	**1.81**
n_e / n_{GW}	1.1	**0.85**
Z_{eff}	1.5	**1.7**
P_{rad} / P_{tot}	0.40	**0.58**
κ, δ	1.74, 0.48	**1.84, 0.5**
q_{95}	3.2	**3.0**
τ_{pulse} / τ_E	15	**110**

⇒ High confidence level in attainment of Q=10 due to targeted R&D

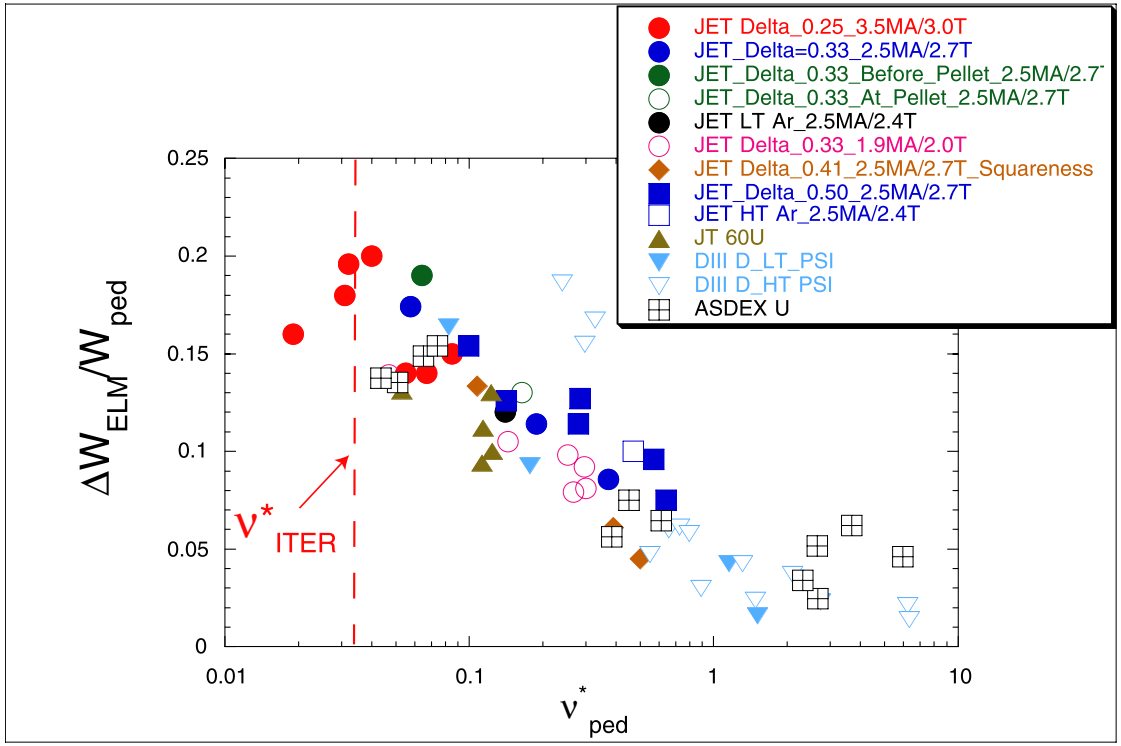
Q=10 Issues: Divertor





- Extensive modelling of power and particle exhaust gives confidence in ITER divertor performance:
  - Peak target power can be limited below 10MWm^{-2} in reference scenarios
  - Installed fuelling and pumping capacity should ensure that core helium capacity can be held below 6%

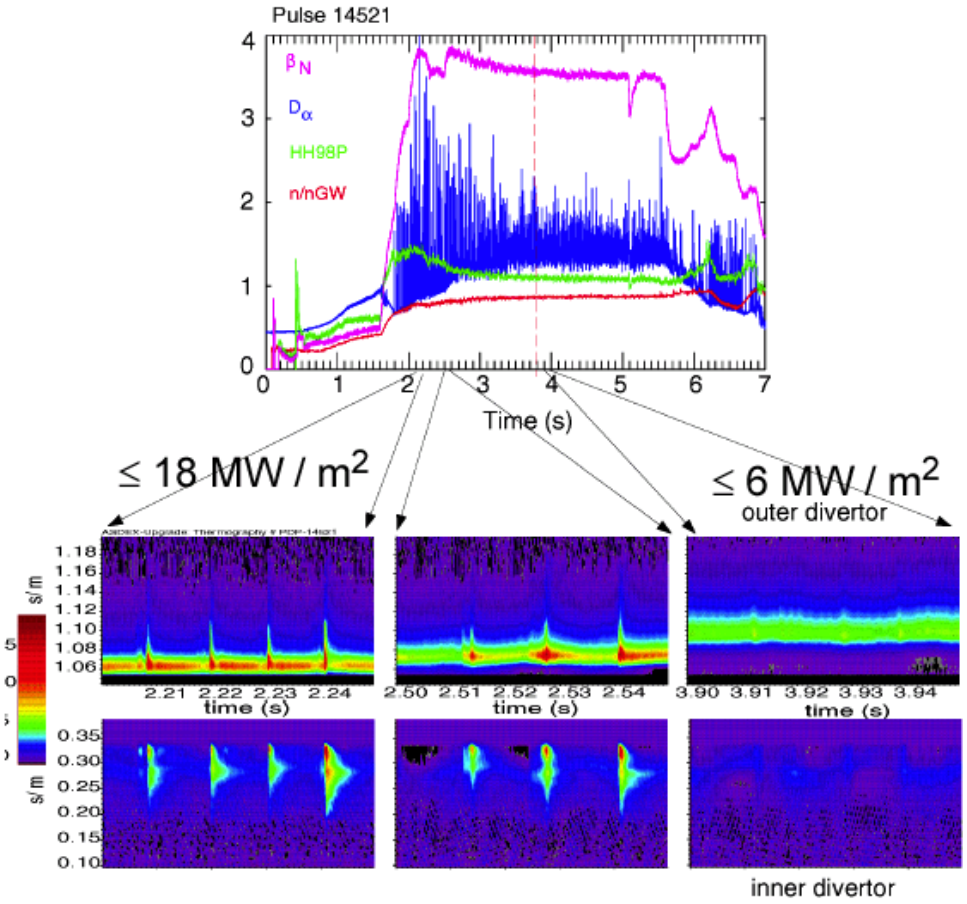
Q=10 Issues: ELMs at Divertor



- Analysis of ELM energy losses from several tokamaks shows that ELM normalized energy losses scale with ν^*_{ped}:
  - underlying physics of this process remains focus of intense R&D
  - extrapolation to ITER indicates that type I ELMs could limit divertor lifetime

Q=10 Issues: Divertor

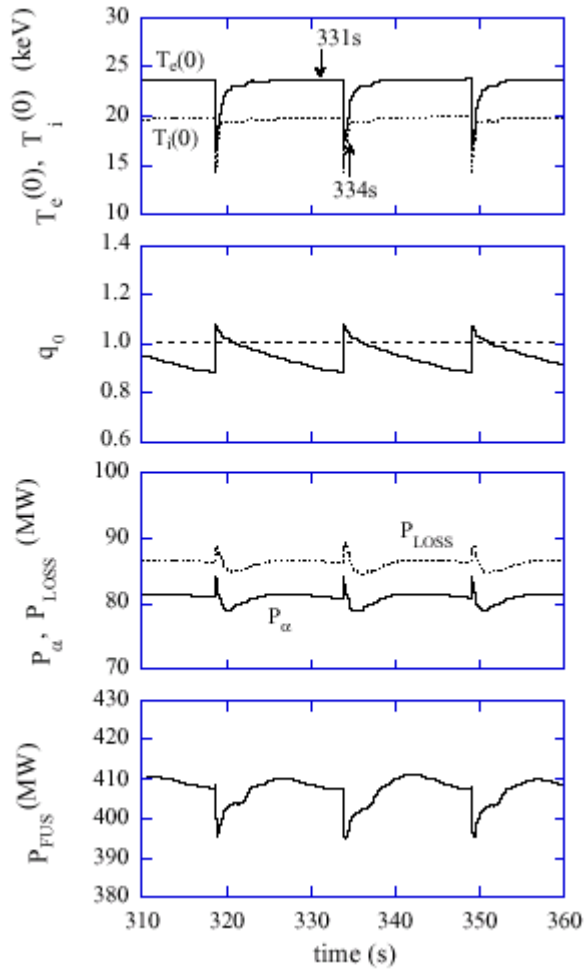
- Ongoing R&D is addressing outstanding divertor and PSI issues for high duty cycle operation:
  - ELM erosion rates under study - type II ELM regime expanded
  - tritium retention process studied in tokamaks and simulators (eg PISCES-B)
  - in-situ control of T-codeposition by surface temperature control under study
  - W-target R&D highly advanced
- These issues must be solved for any type of magnetic fusion power plant



⇒ **Focussed effort starts bearing fruit**

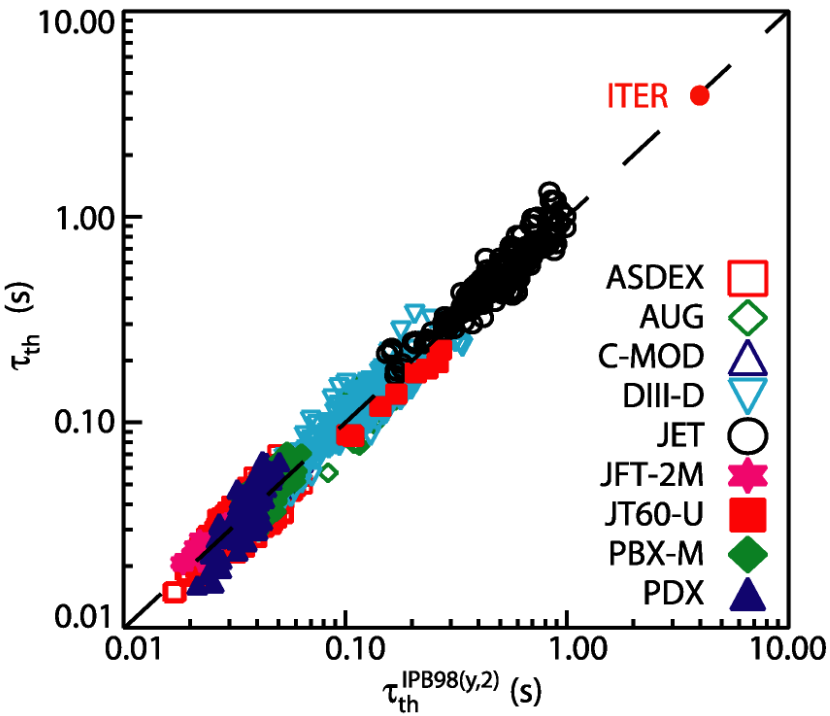
Q=10 Issues: α-Particle Effects

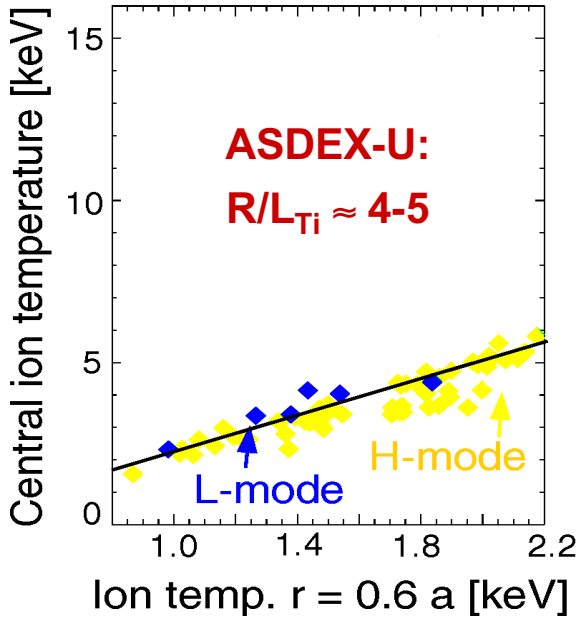
- α-particle confinement:
  - classical confinement good - ferromagnetic inserts reduce ripple to <0.5% (small areas >0.1%)
  - Alfvén modes: for reference scenario (monotonic q-profiles), PENN & Mishka calculations show:
    - linearly stable, or
    - weak distribution of α-particles
  - Fishbones: (marginally) unstable for nominal parameters
- Sawteeth:
  - period extended by α-particle stabilization
  - 30% excursion in T(0)
  - small effects on fusion power (~3%) and heat flux



Q=10 Issues: Extend Baseline Data

⇒ Extend confinement scaling and validate theory



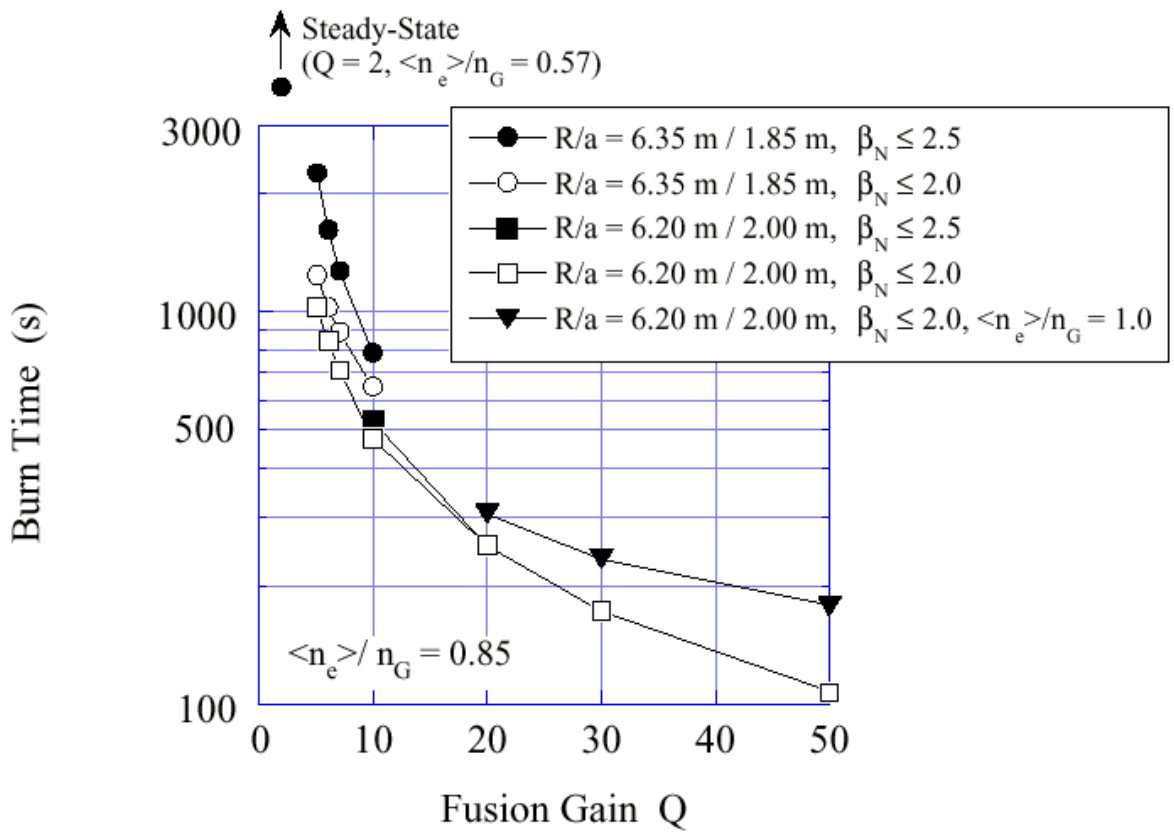


- **Global Confinement:**
  - extend study of core / pedestal contributions

- **Profile stiffness:**
  - extend code validation
  - role of n/n_{GW} vs ν^*
  - role of self-generated flows
  - electron transport

Hybrid Operation: Q > 5

⇒ Conservative scenario for technology testing



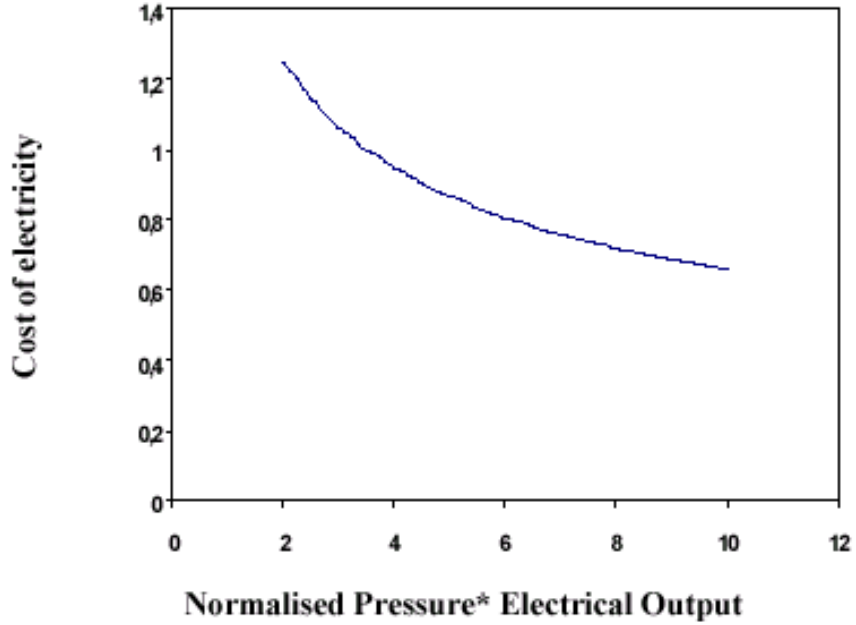
Parameter	Hybrid #3
R (m)/a (m)	6.35/1.85
B_T (T)	5.17
I_P (MA)	12.6
q_{95}	3.1
$\langle n_e \rangle$ ($10^{20} m^{-3}$)	1.1
n_e/n_G	0.94
$\langle T_i \rangle$ (keV)	8.5
$\langle T_e \rangle$ (keV)	9.7
β_N	2.3
P_{FUS} (MW)	500
P_{NBI} (MW)	60
P_{RF} (MW)	40
$Q = P_{FUS}/(P_{NB}+P_{RF})$	5.0
τ_E (s)	2.26
$H_H(y,2)$	1.0
β_p	1.01
l_i (3)	0.81
V_{loop} (mV)	46
Burn flux (Vs)	64
Burn time (s)	1380
I_{CD}/I_P (%)	29
I_{BS}/I_P (%)	21
γ_{20}^{TOT} ($10^{20} A/Wm^2$)	0.26

Advanced Tokamak Operation

⇒ Satisfy steady-state objective

- Major objective is to prepare DEMO (device having characteristics of a commercially viable reactor)
  - 'blue ribbon' fast track panel
  - fusion industry committee

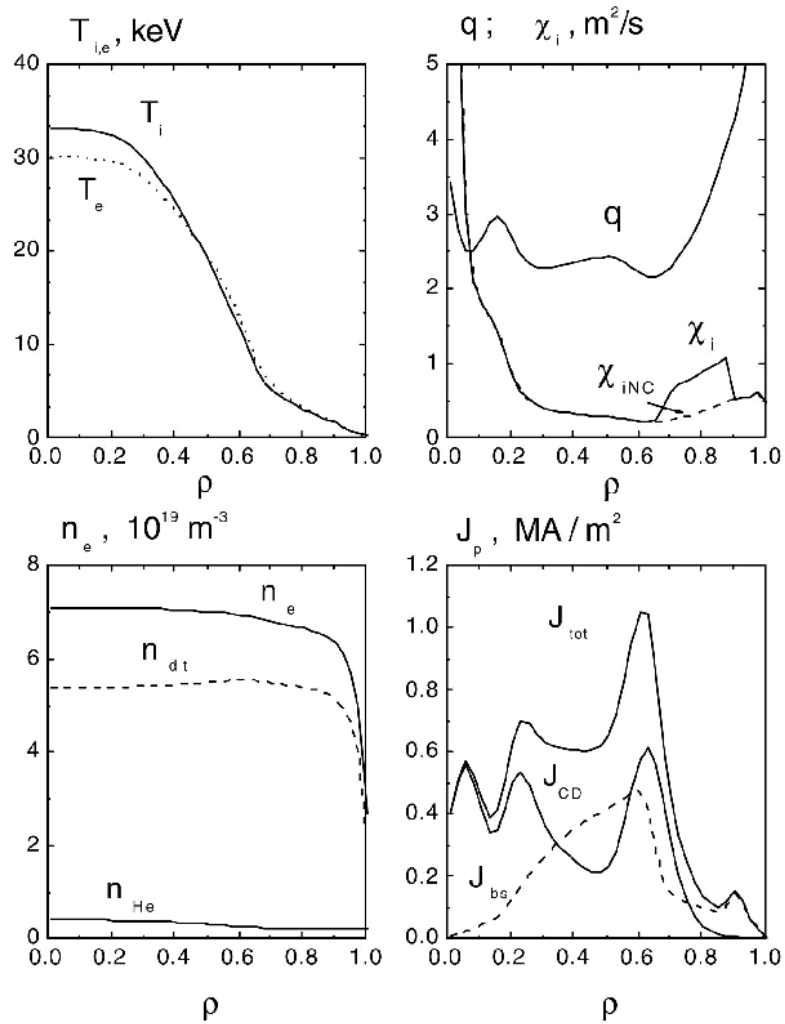
- Associated physics issues match ITER's capabilities
  - α-physics compatibility
  - long pulse aspects:
    - current profile evolution
    - plasma-wall interactions
  - α-heating power > current drive power ⇒ controllability



	ITER-baseline	ITER-steady	1st generation reactor designs	"advanced" reactor designs
β_n	1.8	3.1	3.5 - 4	> 4
<β> [%]	2.5	2.9	2.2 - 3	3 - 5

A Steady-State Scenario in ITER

- A range of scenarios has been explored with varying assumptions on core shear
  - results are illustrative
  - further development is required
- ASTRA calculations of plasma profiles for an ITER steady-state scenario:
  - "weak central shear"
  - I_p=9MA, q_{95}=5.3
  - $H_{98(y,2)}$=1.6, β_N=2.95
  - f_{bs}=48%, f_{CD}=52%
  - $P_{RF}+P_{NB}$=29+30MW, P_{fus}=356MW



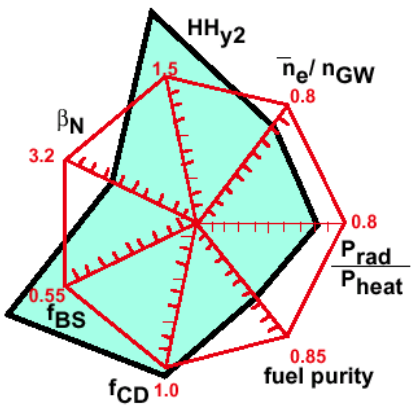
Requirements on R&D

⇒ Extrapolation and extension of regime

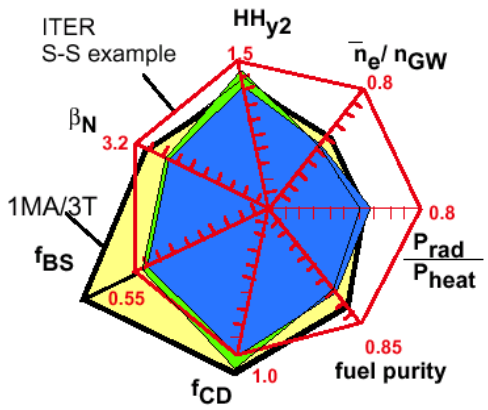
JT-60U '7-fold way" diagrams illustrate approach to ITER steady-state target in dimensionless parameters - require:

- higher n/n_{GW}
- lower q_{95}

JT-60U RS

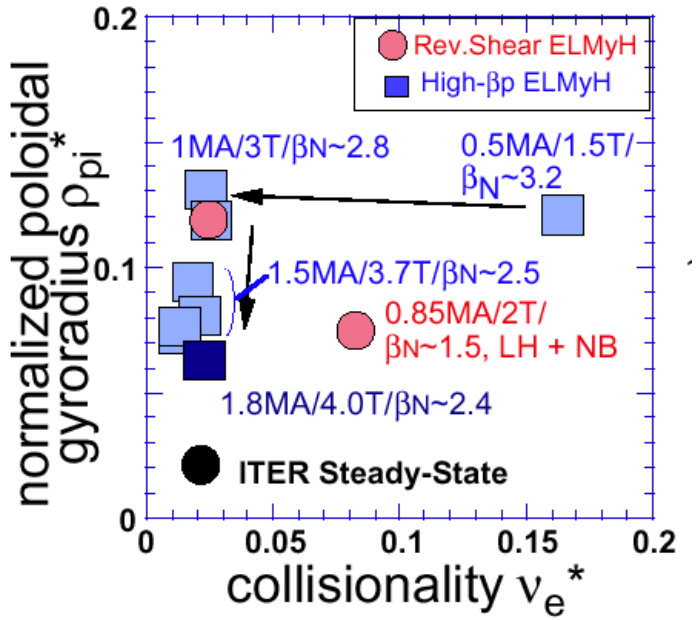


JT-60U High-β_p



ITER and Power Plant:

higher n/n_{GW} but lower ν^*



Requirements on R&D

Self-consistency of parameters and profiles:

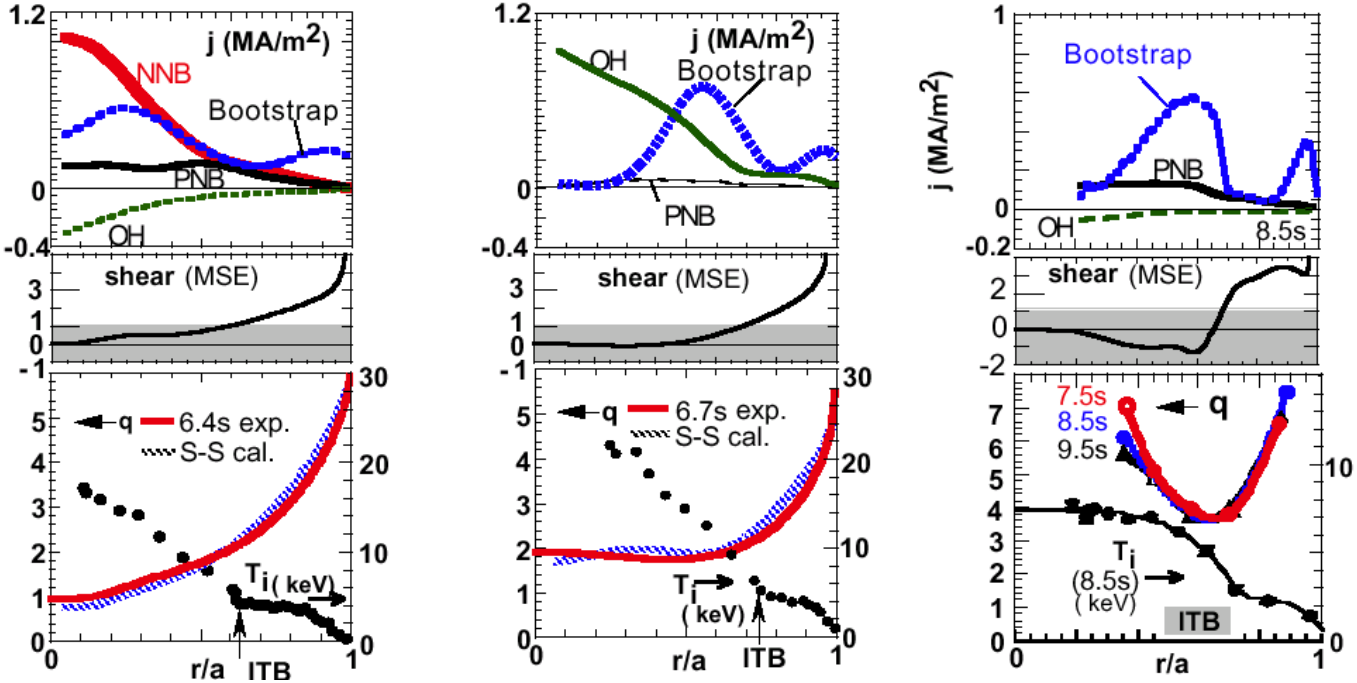
⇒ a range of "advanced" scenarios exists

JT-60U

central CD+ bootstrap
q_{95}=4.8, β_N=2.5 HH_{y2}=1.4

bootstrap
β_N=2.8 HH_{y2}=1.5

broad CD + high bootstrap
q_{95}=9.3, β_N=2.2 HH_{y2}=2.2



Requirements on R&D

Self-consistency of parameters and profiles:

⇒ a range of "advanced" scenarios exists

ASDEX-U:

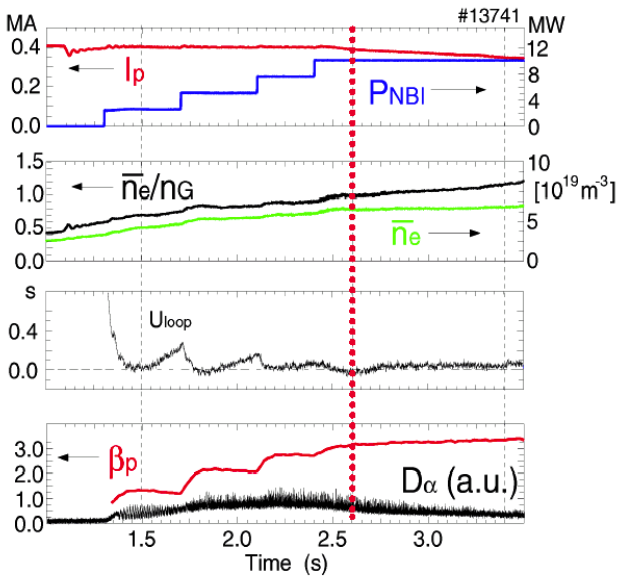
high-β_p, monotonic-q

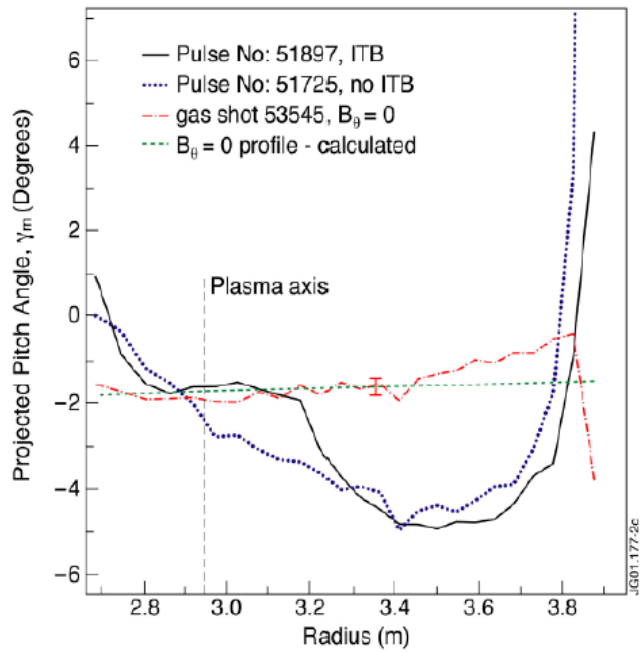
high n/n_{GW}, but poor I_{bs} alignment

JET:

LHCD - current "hole"

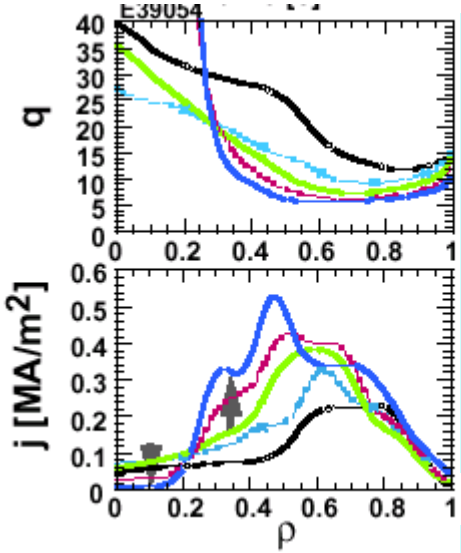
good I_{bs} alignment, but α-confinement?





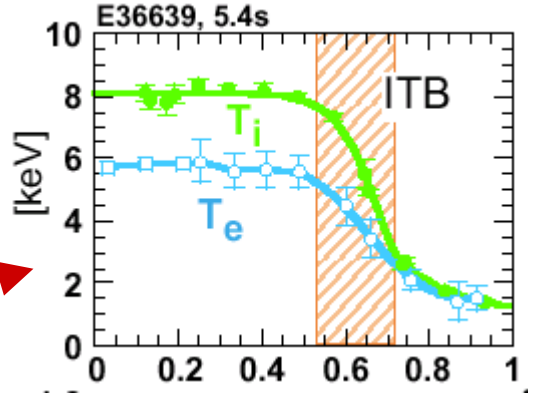
Requirements on R&D

Current holes as extreme of reversed shear

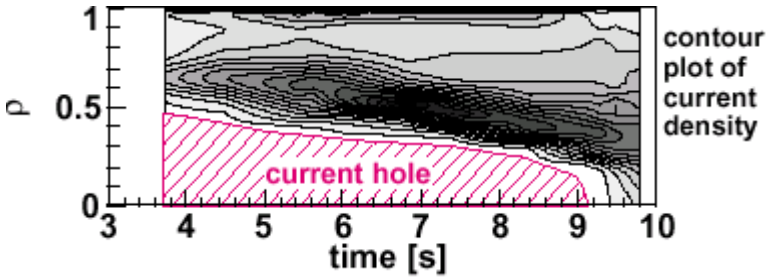


JT-60U:

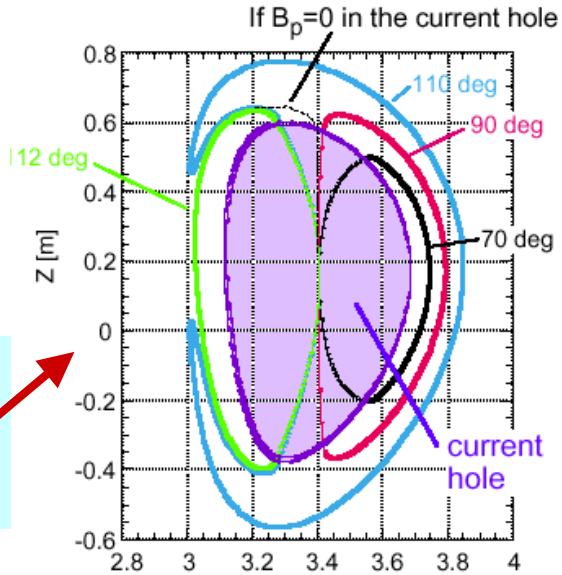
- current hole generated only by bootstrap current:
  - efficient I_{bs} generation in low-B_p region
  - high energy density inside barrier



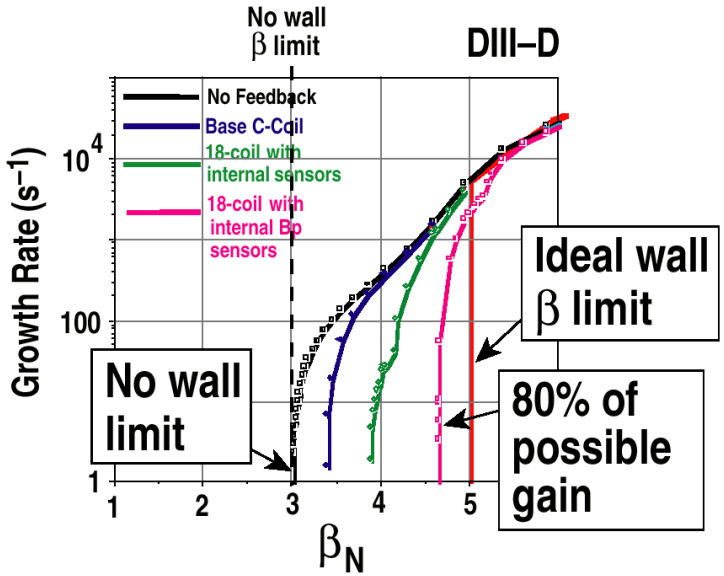
- residual V_{loop} causes decay of j(r) distribution

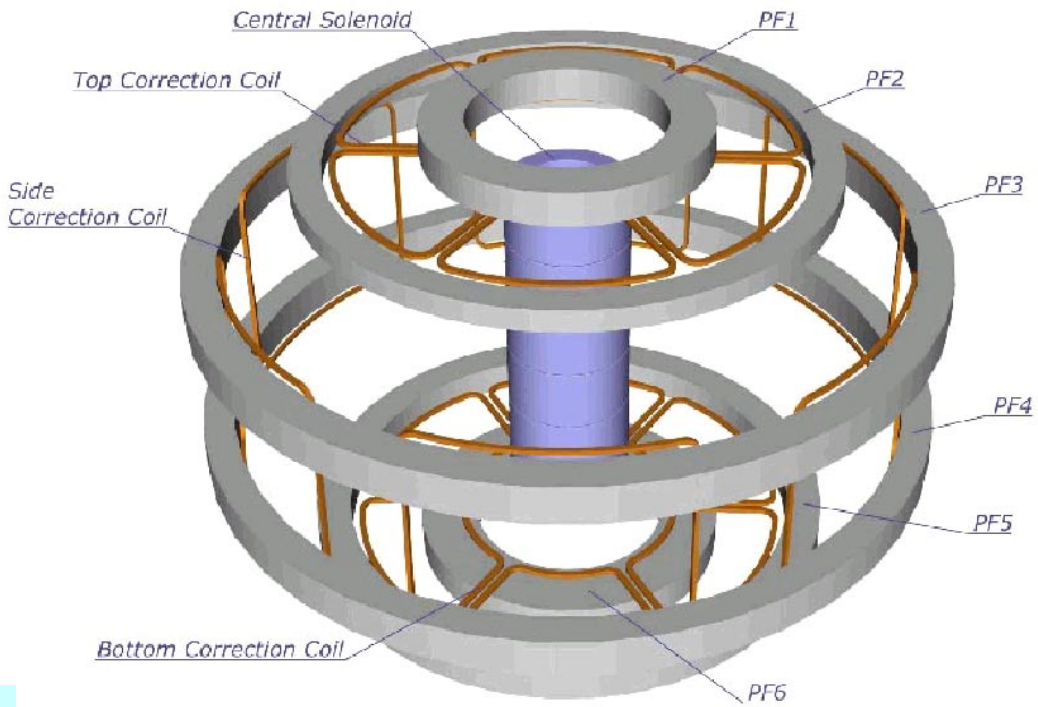


- large excursions of 4keV ions in zone where B_p is zero



High-β Stability





Advanced scenarios at high β_N require RWM feedback stabilization:

- **DIII-D calculations illustrate possible gain**

ITER error field correction and RWM control coils

α-Particle Physics in Advanced Scenarios

- α-particle confinement and heating more challenging than in conventional scenarios:
  - Ferromagnetic inserts ensure good classical confinement

	Inductive		Weak RS (#4)		Strong RS	
	No FI	With FI	No FI	With FI	No FI	With FI
Total particle loss fraction (%)	2.15	negligible	6.5	0.08	21	0.75
Total power loss fraction (%)	0.65	negligible	2.5	0.04	9.3	0.13
Peak FW heat load (MWm^{-2})	< 0.1	negligible	0.23	0.005	0.8	0.025
Plasma current (MA)	15		10		10	

- Response of plasma to α-heating is a key issue for advanced scenarios:
  - predominantly electron heating & α-heating profile essentially determines pressure profile
  - high performance plasmas must be maintained in non-linear equilibrium involving pressure, current, thermal diffusivity profiles

α-Particle Physics in Advanced Scenarios

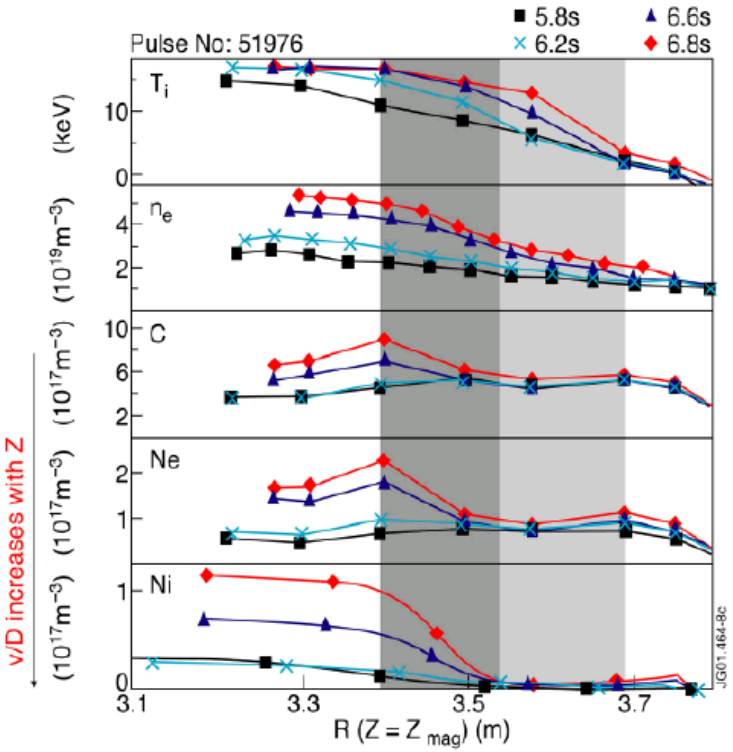
Excitation of AEs and their influence on α-particle confinement is a central question for viability of advanced scenarios

- **α-particle parameters in ITER allows access to relevant range where α-driven instabilities can be studied:**
  - **FEAT α-parameters similar to those of ITER-98**

Parameter	NBI	ICRH	α's (TFTR)	α's (JET)	α's (1998)	α's (FEAT)
$P_f(0)$ [MWm^{-3}]	3	1–3	0.3	0.16	0.3	0.44
δ_f/a	0.05	0.3	0.3	0.34	0.05	0.08
$n_f(0)/n_e(0)$ [%]	13	1-10	0.3	0.17	0.3	0.8
$\beta_f(0)$ [%]	0.9	1-3	0.26	0.3	0.7	1.1
$\langle\beta_f\rangle$ [%]	0.4	0.5	0.03	0.04	0.2	0.16
max $\lvert R.\nabla\beta_f\rvert$	0.04	≈ 0.1	0.02	0.016	0.06	0.08
$v_f/v_A(0)$	0.35	≈ 1-2	1.6	1.4	1.9	1.8

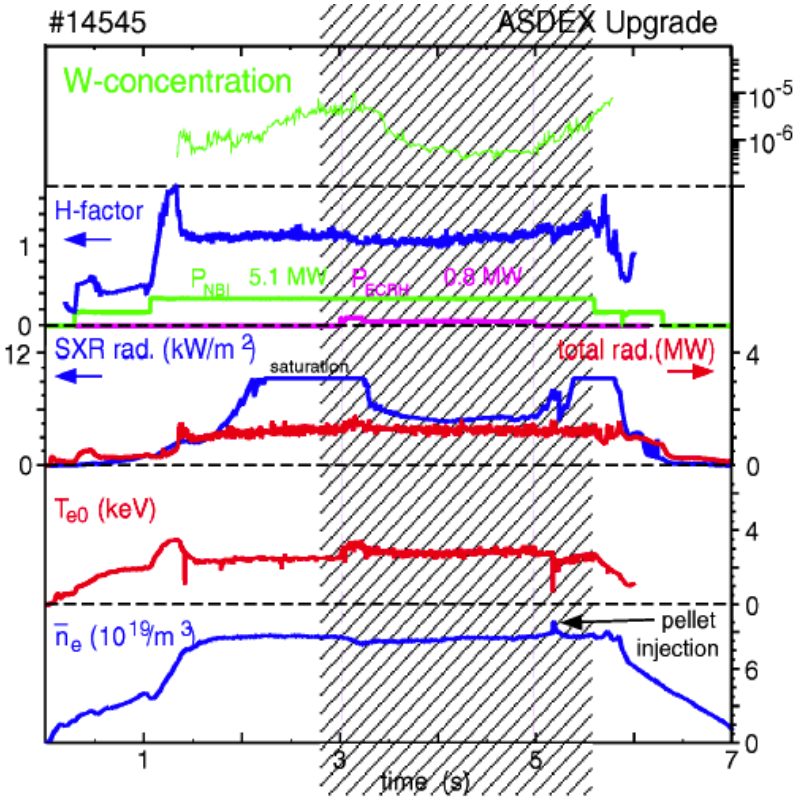
- **"Synergy" between redistribution of α-particles due to AEs and TF ripple losses will need to be addressed**

Divertor Compatibility: Impurity Control



- **Impurity density in ITB plasmas in JET (also JT-60U):**
  - **no accumulation for low and medium Z**
  - **accumulation of high-Z**

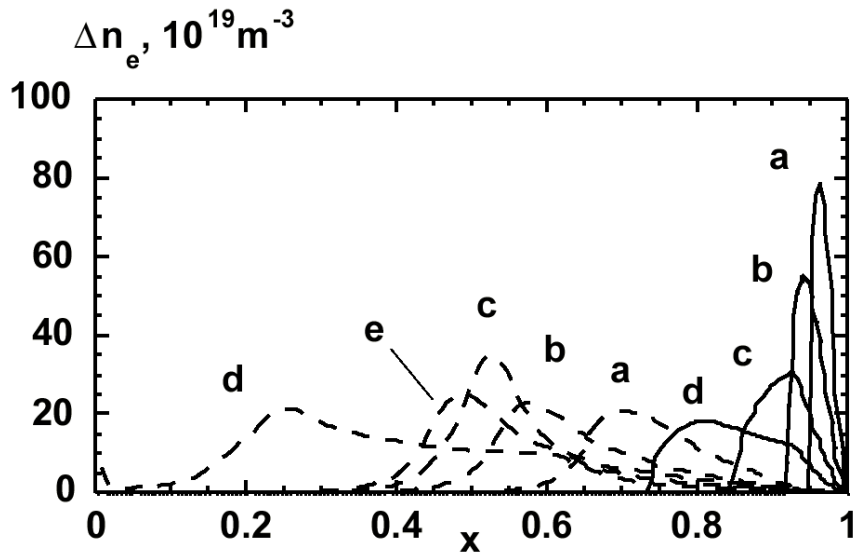
- **W-experiments in ASDEX-U:**
  - **central (electron) heating suppresses accumulation (α's !)**



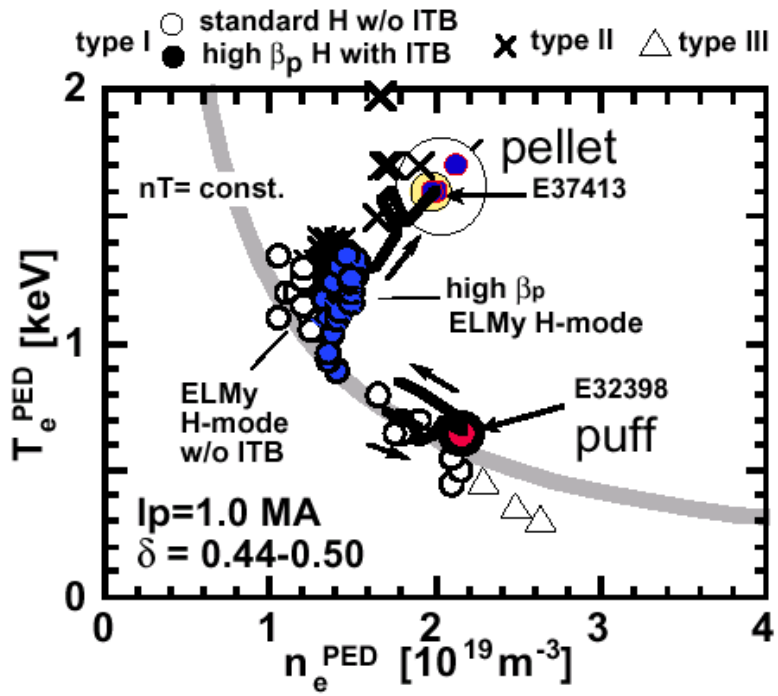
Fuelling - HFS Pellet Launch

type	number of injectors	repetition frequency	size	velocity	pulse length capability
high field side centrifuge	2 (3)	7 – 50Hz	3 - 6 mm	< 0.5 km/s	3000 s

- **HFS launch beneficial for high-β_p plasmas in JT-60U:**
  - **Influence on reversed shear modes still to be explored**

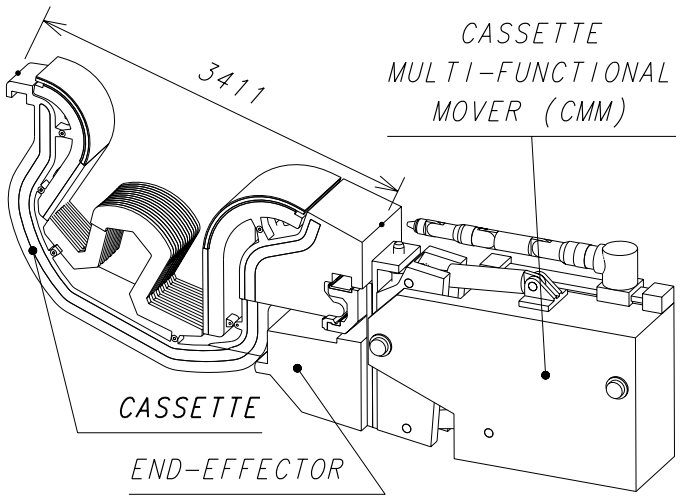


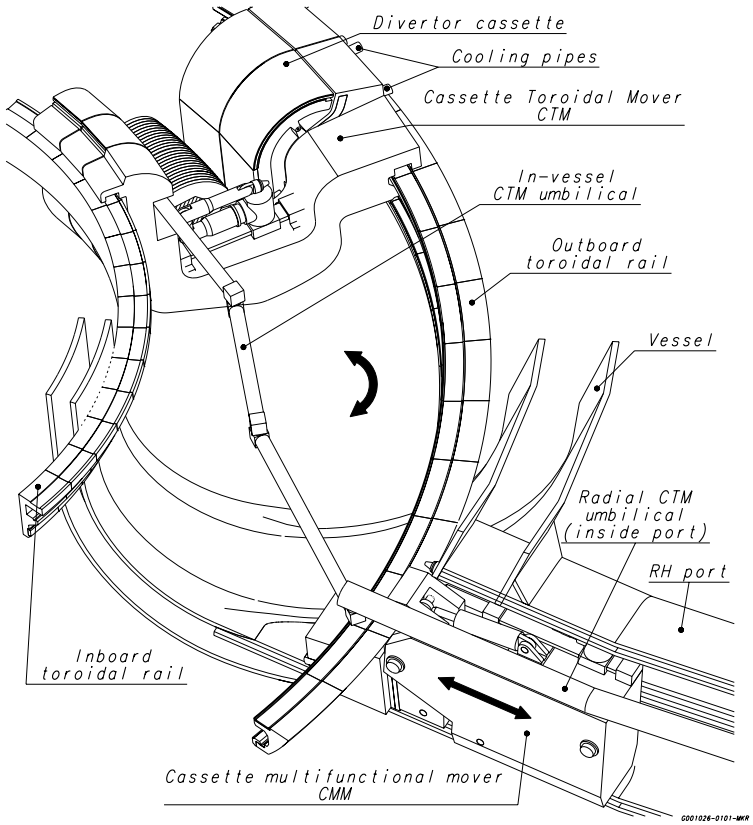
- **Modelling indicates inward shift of mass deposition with respect to ablation in ITER**



Divertor Flexibility

Operational flexibility is achieved through divertor maintenance and exchange capability



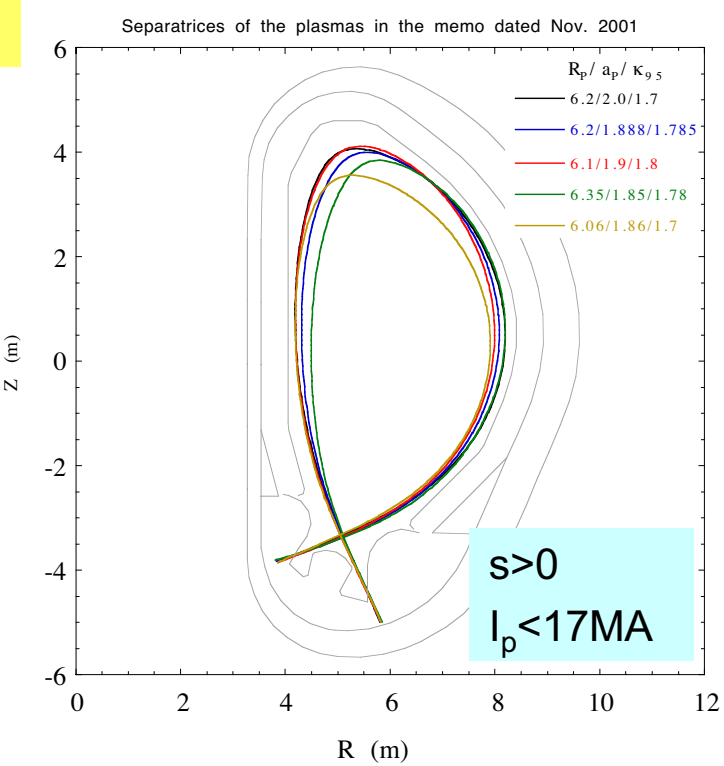


- **For refurbishment and design improvements**
  - **Divertor cassette system allows divertor exchange within 6 months**

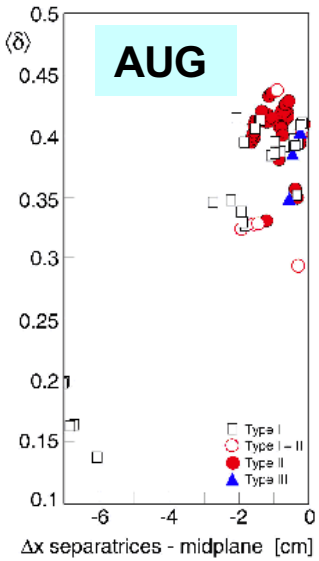
Equilibrium Flexibility

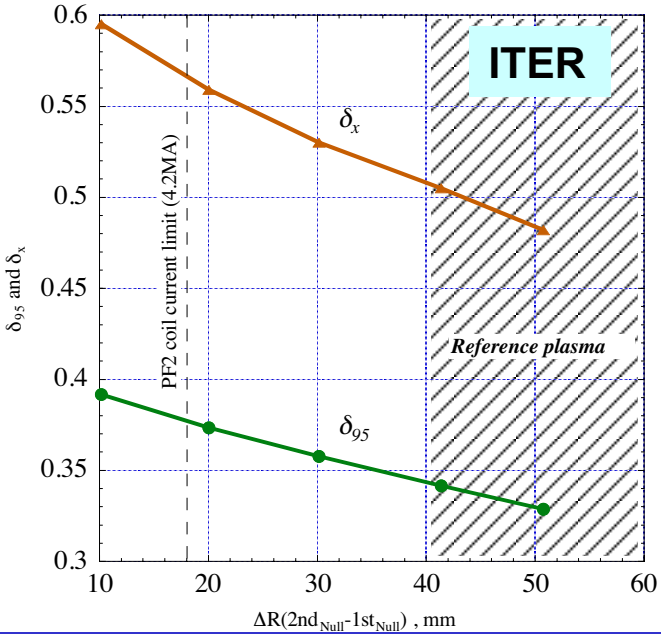
Increased shaping relative to ITER-98 can be extended to accommodate important developments

	FDR	FEAT
κ_{95}/κ_x	1.6 / 1.76	1.7 / 1.86
δ_{95}/δ_x	0.24 / 0.31	0.35 / 0.5



DNX proximity ⇒ type II ELMs (?)





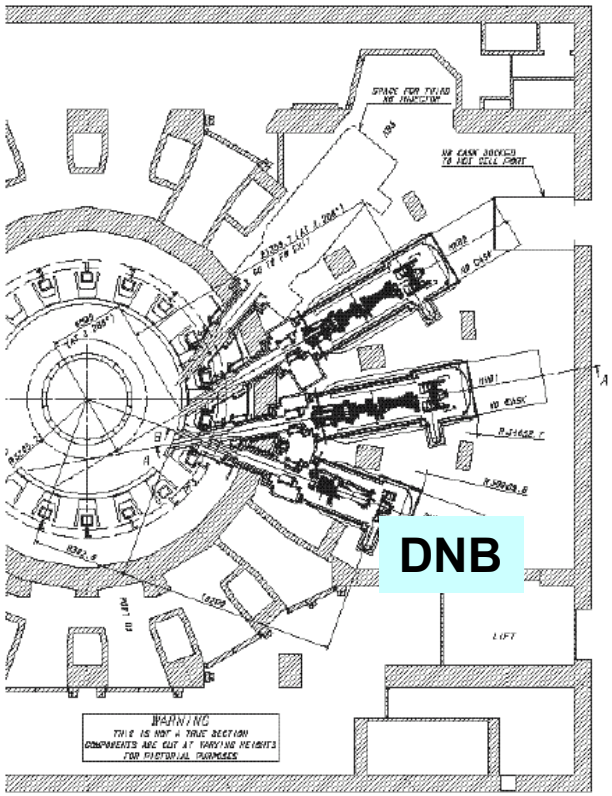
Advanced scenarios → stronger shaping

l_i	0.6	0.4
$k_{95,ma}$	<2	<2.1

Heating and Current Drive Systems

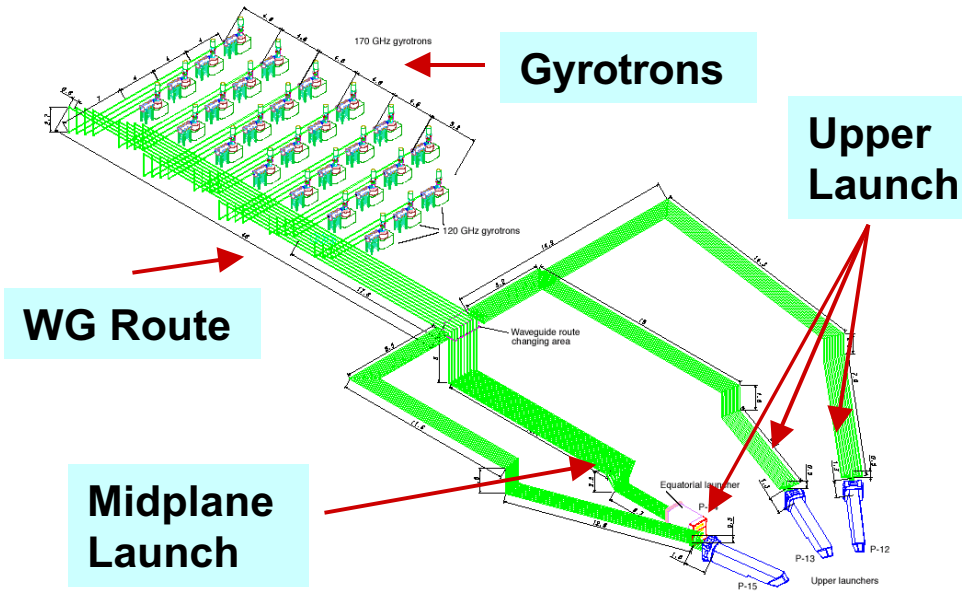
Heating System	Stage 1	Possible Upgrade	Remarks
NBI (1MeV –ive ion)	33	16.5	Vertically steerable (z at Rtan -0.42m to +0.16m)
ECH&CD (170GHz)	20	20	Equatorial and upper port launchers steerable
ICH&CD (35-55MHz)	20		$2\Omega_T$ (50% power to ions Ω_{He3} (70% power to ions, FWCD)
LHH&CD (5GHz)		20	$1.8<n_{par}<2.2$
Total	73	130 (110 simultan)	Upgrade in different RF combinations possible
ECRH Startup	2		
Diagnostic Beam (100keV, H^-)	>2		

NBI Layout



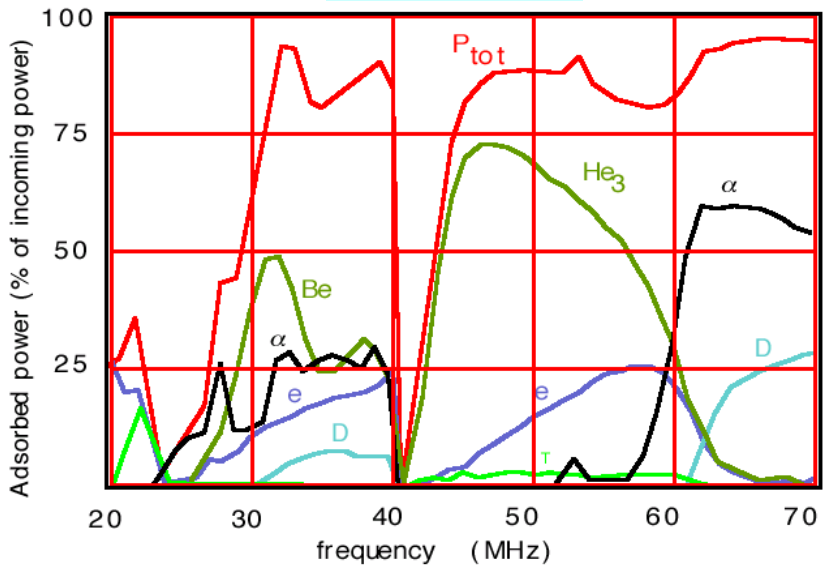
P_{aux} for Q=10 nominal scenario: 40MW

Heating and Current Drive Systems



ECH&CD System

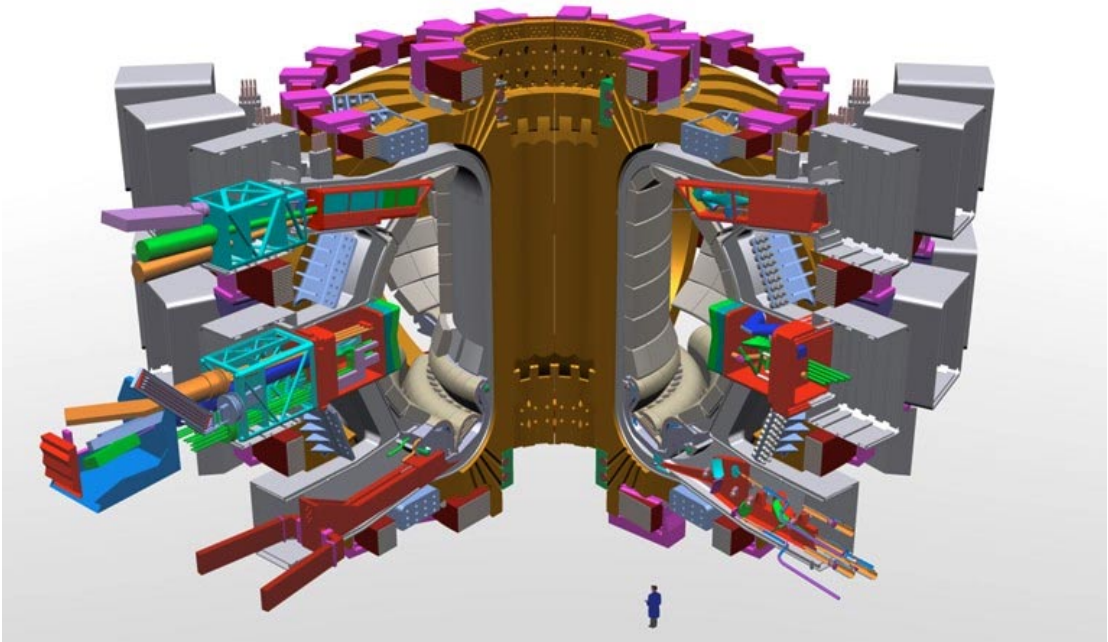
ITER ω-range



ICH power absorption by species

- **ITER RF System R&D**
  - **170GHz gyrotron and diamond window for ECH**
  - **ITER-like RDL ICH antenna to be tested in JET**
  - **ITER-like PAM launcher to be tested in FTU and Tore Supra**

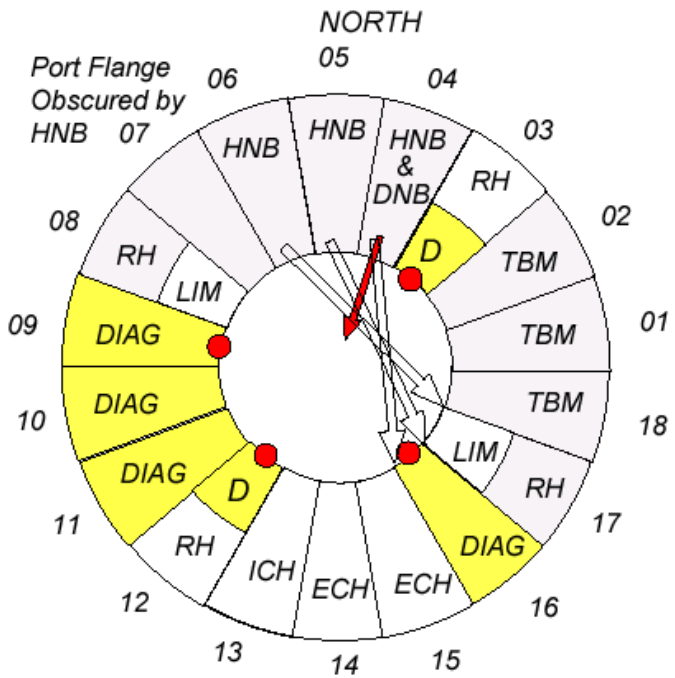
Diagnostic Systems



- **An extensive range of diagnostic systems is foreseen:**
  - **Diagnostics required for protection, control and physics studies**
  - **Access through equatorial, upper and divertor ports**
  - **Diagnostic Neutral Beam for active spectroscopy (CXRS, MSE ….)**

Diagnostic Systems

EQUATORIAL PORT



3 Wide angle viewing/IR
CXRS (with DNB)
MSE (with heating NB)
H-alpha/Vis spect (Div).

4 DNB

7 Obscured port

8 RH plus Limiter
Neutron flux monitor

9 Wide angle viewing/IR
Tor./Intefer. polarimeter
ECE
Fast Wave Reflectometry
(possibly) MSE

10 LIDAR Thomson Scattering
Polarimeter

11 X-ray Cryst spec
NPA
VUV (main & div.)
Reflectometry

12 Wide angle viewing/IR
H-□ /Vis. spec (upper edge)
Vis. continuum array

16 Wide angle viewing/IR
Radial Neutron Camera
Bolometry
Soft x-ray array
Divertor Impurity (div 16)

17 RH plus Limiter
Neutron flux monitor
Neutron Act syst (foil & ^{16}N)

Unassigned:
Collective scattering

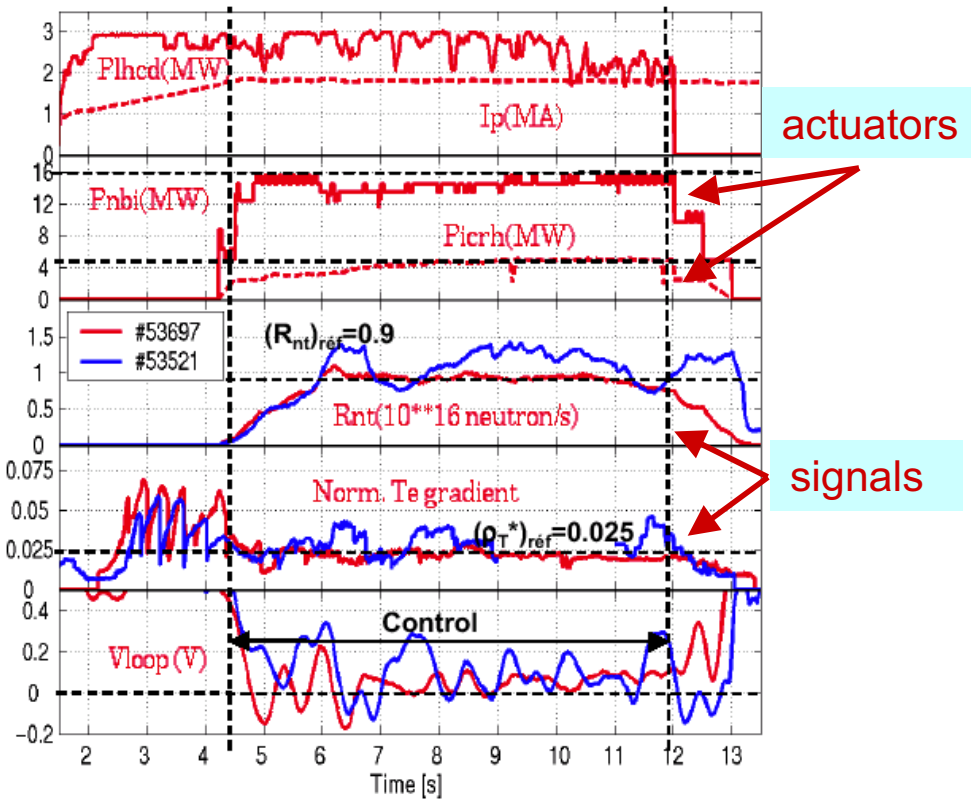
Example of diagnostic distribution in midplane

Control Capability

Extensive H&CD system and Diagnostic capability allows possibility of sophisticated control techniques

- **Long-pulse feedback control of JET ITB discharges:**
  - **LHCD used to delay current profile development**
  - **ITB existence criterion and control parameter:**

$$\rho_T^* = \rho_s / L_T > \rho_{ITB}^*$$



Pulse Length and Duty Cycle

Scenario	Burn (s) *
Inductive (reference)	500
Hybrid	1000
Steady-state	3000 **

* repetition time = 4 × burn time

** limited by external cooling capacity (at present)

- **ITER has high availability:**
  ⇒ ample experimental time and opportunities

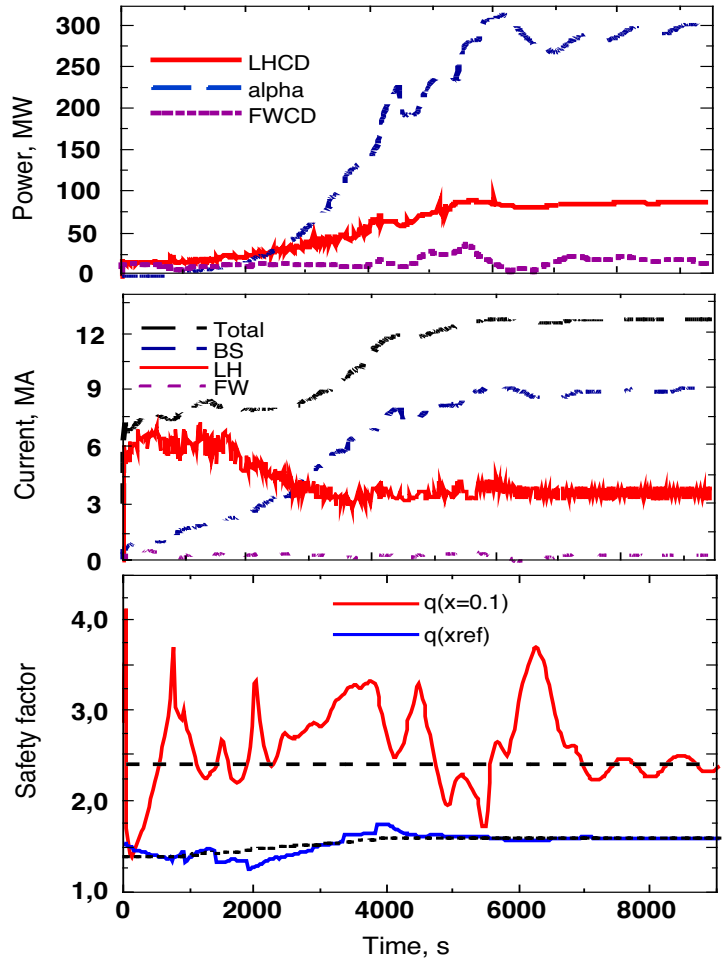
- **Current diffusion requires**

$$\tau \sim \tau_R$$

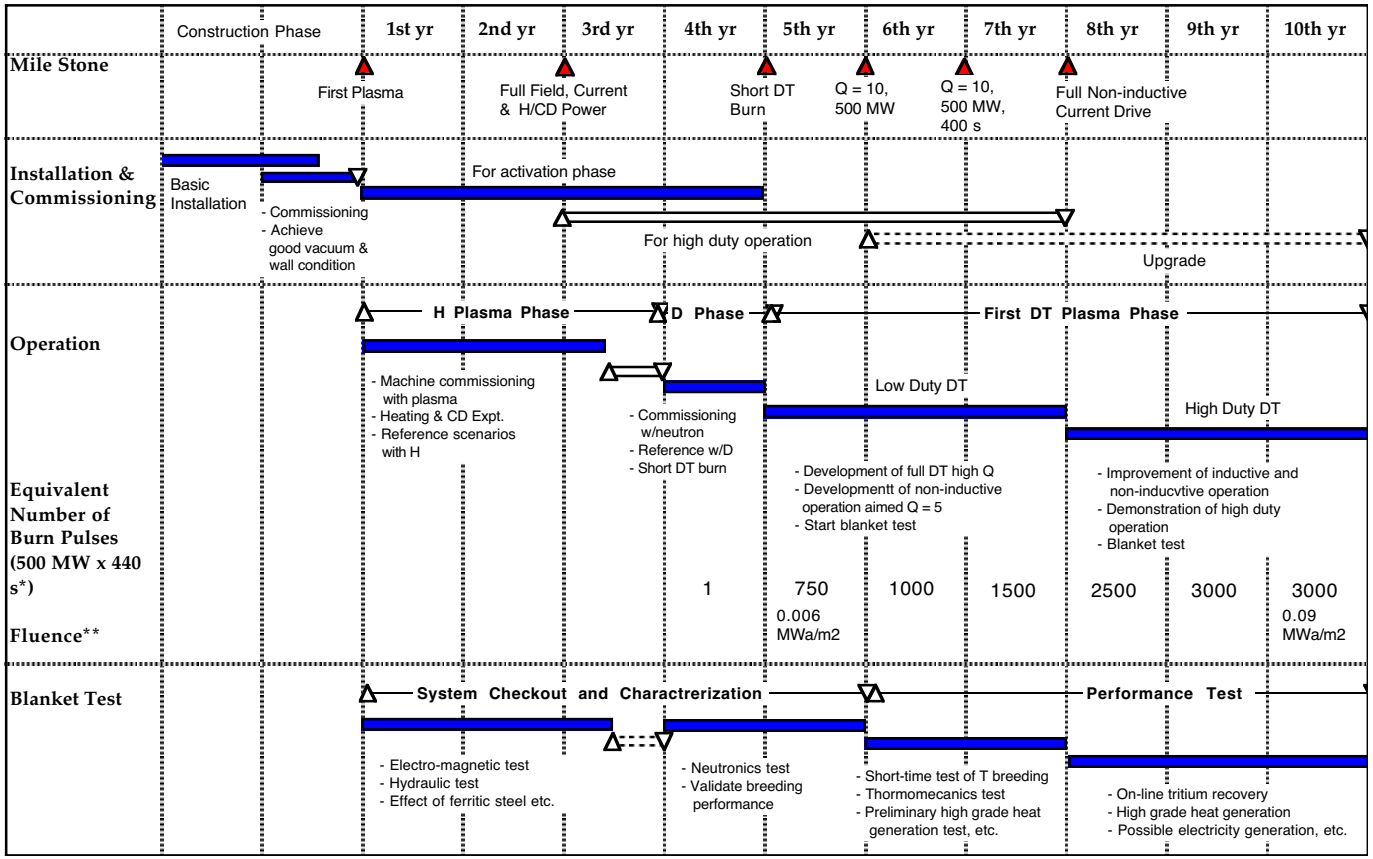
- **But execution of control implies**

$$\tau \gg \tau_R$$

Moreau: ITER-98 simulation



Plasma Operation Timeschedule



- **Operation plan for first 10 years foresees:**
  - DT operation beginning in 4th operational year
  - 6 years of development and improvement of DT burning plasma scenarios

Conclusions

- **ITER has many assets as a burning plasma experiment**

- **To fulfill its missions ITER must carry out an ambitious and exciting physics programme**
- **Its essential design features give it the capability to do this:**
  - pulse length and duty cycle
  - flexible heating and current drive system
    - total power
    - variety of systems
  - diagnostic access and facilities
  - additional plasma engineering systems
    - inside pellet launch
    - RWM feedback and error field control
  - equilibrium shape flexibility
  - divertor and first wall exchange capability