ITER as a Physics Experiment

K.Lackner, D. Campbell and many others

EFDA-CSU

D-85748 Garching

ITER exploitation phase subdivided into two sub-phases*)

- the first 10 years corresponding to an experimental physics oriented programme,

*) EDA Final Design Report

- the following 10 years to an intensive, technology oriented, use of the facility.

ITER´s role

- **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 a-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 a-confinement
- controllability

– satisfy steady state objective
– prepare DEMO

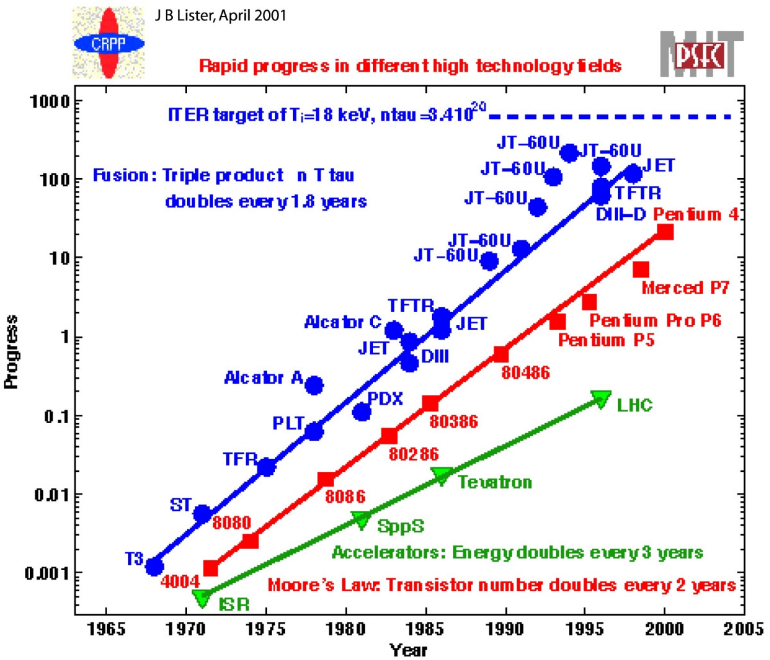
Standard inductive scenarios

- **verify & extend our scalings and theory models (confinement, H-mode access, ELMs, NTMs..)**
- **qualify a-particle heating as a heating method**
- **high power/long pulse (on wall equilibration time) test of plasma wall interaction (incl. tritium inventory control)**

maintain momentum:

demonstrate milestone

- o fusion community must show public&politics identifiable progress
- o needed also for continuing support of alternatives



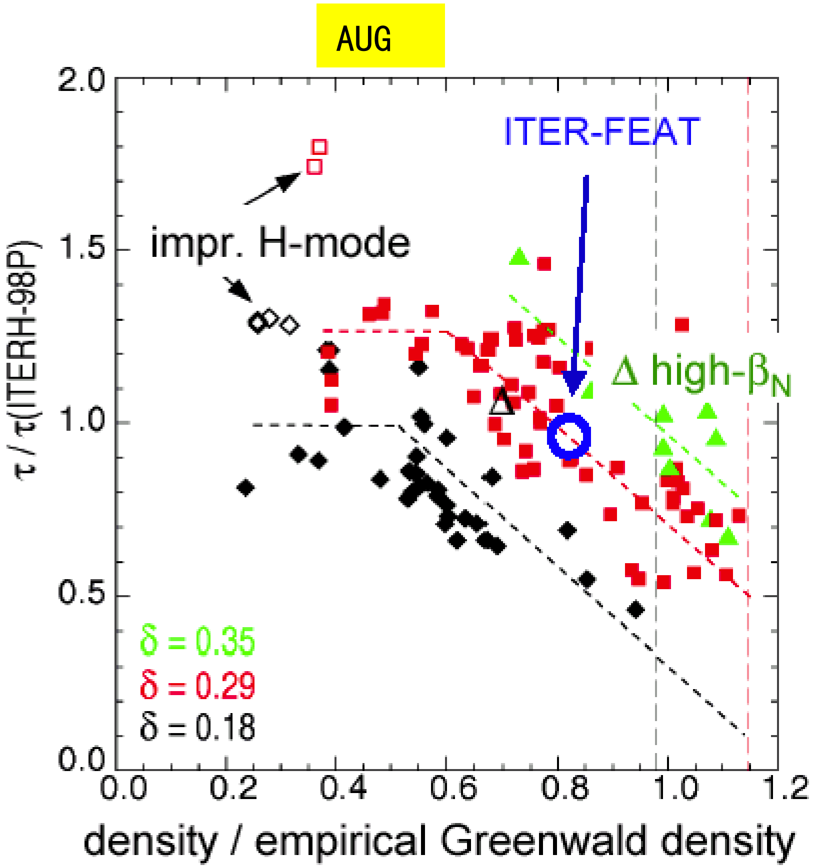
Q= 10 reference scenario(s): milestone

Parameter	400 MW	560 MW	260 MW
R/a (m/m)	6.2/2.0	←	←
κ_{95}/δ_{95}	1.7/0.33	←	←
B_T (T)	5.3	←	←
I_P (MA)	15.0	←	←
q_{95}	3	←	←
$\langle n_e \rangle$ ($10^{20}m^{-3}$)	1.01	1.18	0.83
$\langle n_e \rangle / n_G$	0.85	1.0	0.7
$\langle T_e \rangle$ (keV)	8.8	9.0	8.7
$\langle T_i \rangle$ (keV)	8.0	8.2	7.9
P_{FUS} (MW)	400	560	260
$P_{NB} + P_{RF}$ (MW)	33 + 7	33 + 23	17 + 9
Q	10	←	←
P_{RAD} (MW)	47	71	30
$P_{LOSS}/P_{L\text{-}H}$	1.8 (87/48)	2.4 (124/53)	1.3 (55/42)
β_N	1.8	2.1	1.4
β_P	0.65	0.77	0.52
li (3)	0.84	0.84	0.85
τ_E (s)	3.7	3.1	4.7
$H_{H98(y,2)}$	1.0	←	←
τ_{He}^{*}/τ_E	5.0	←	←
$f_{He,axis/ave}$ (%)	4.3/3.2	4.1/3.1	4.1/3.1
$f_{Be,\ axis}$ (%)	2.0	←	←
$f_{Ar,\ axis}^{*1}$ (%)	0.12	0.16	0.10
$Z_{eff,\ ave}$	1.66	1.77	1.60
V_{loop} (mV)	75	75	82

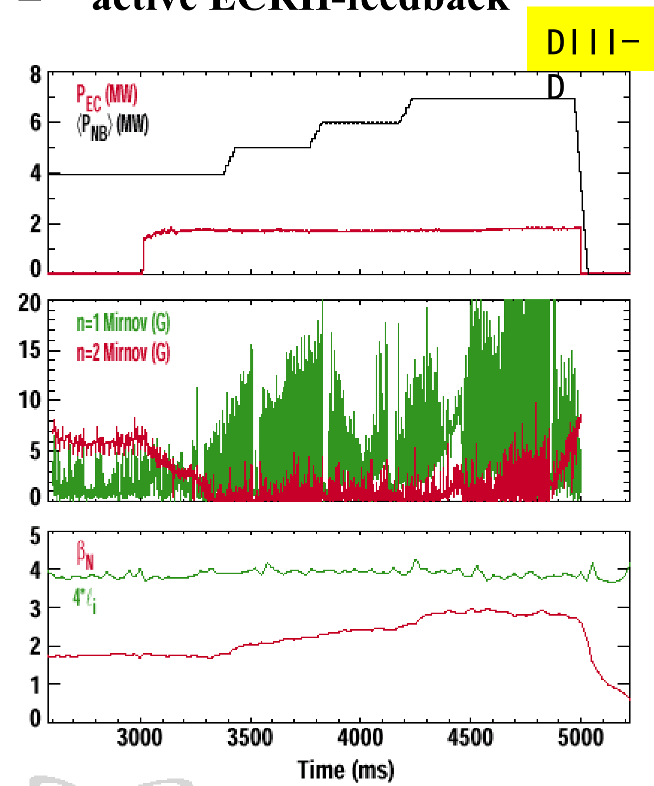
conservative requirements

high confidence level in attainment of Q =10 results of targeted R&D

- **previous major concern: high H-factor at $n/n_{GR} > 0.85$**

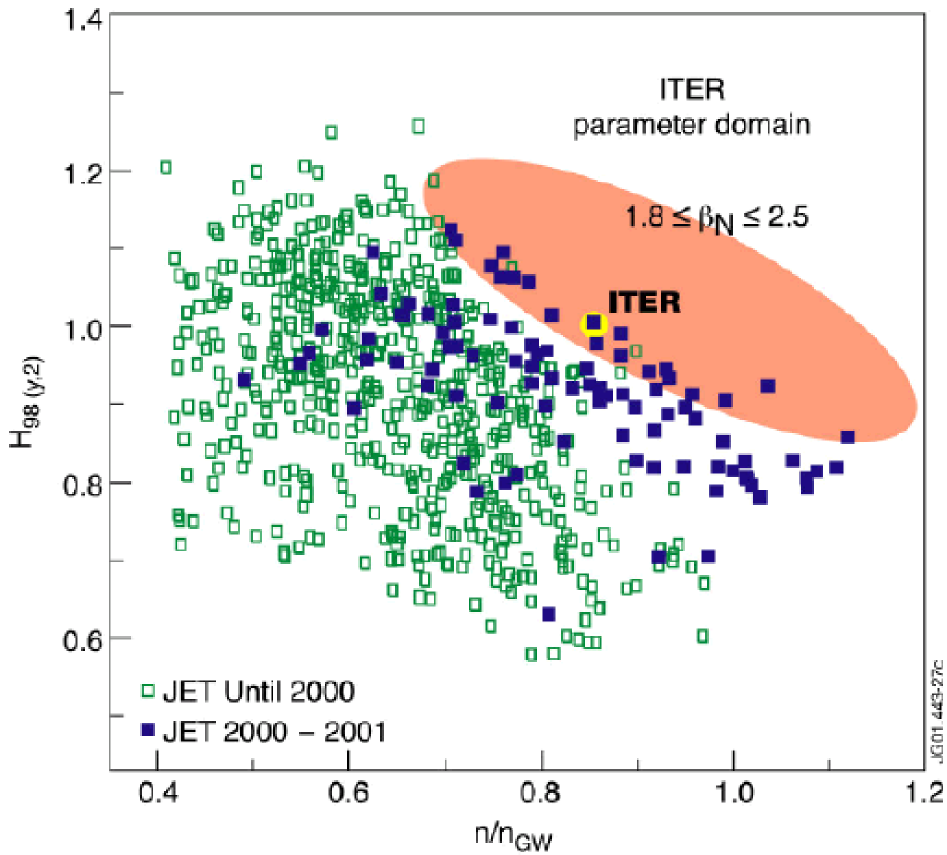


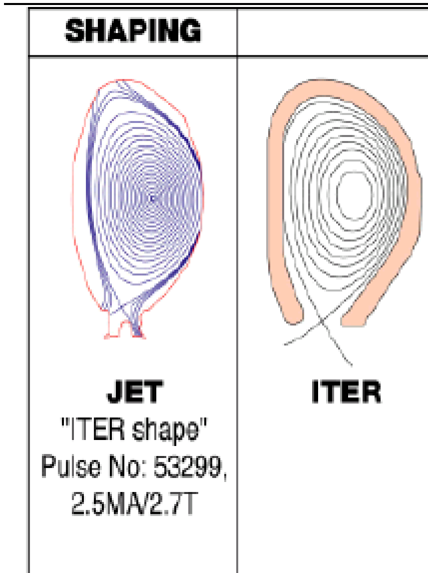
- **NTMs:**
  - **active ECRH-feedback**



  - **self-limitation: FIR-modes (AUG/JET)**
  - **control of sawteeth (JET)**

Q =10: ITER-simulation discharges on JET



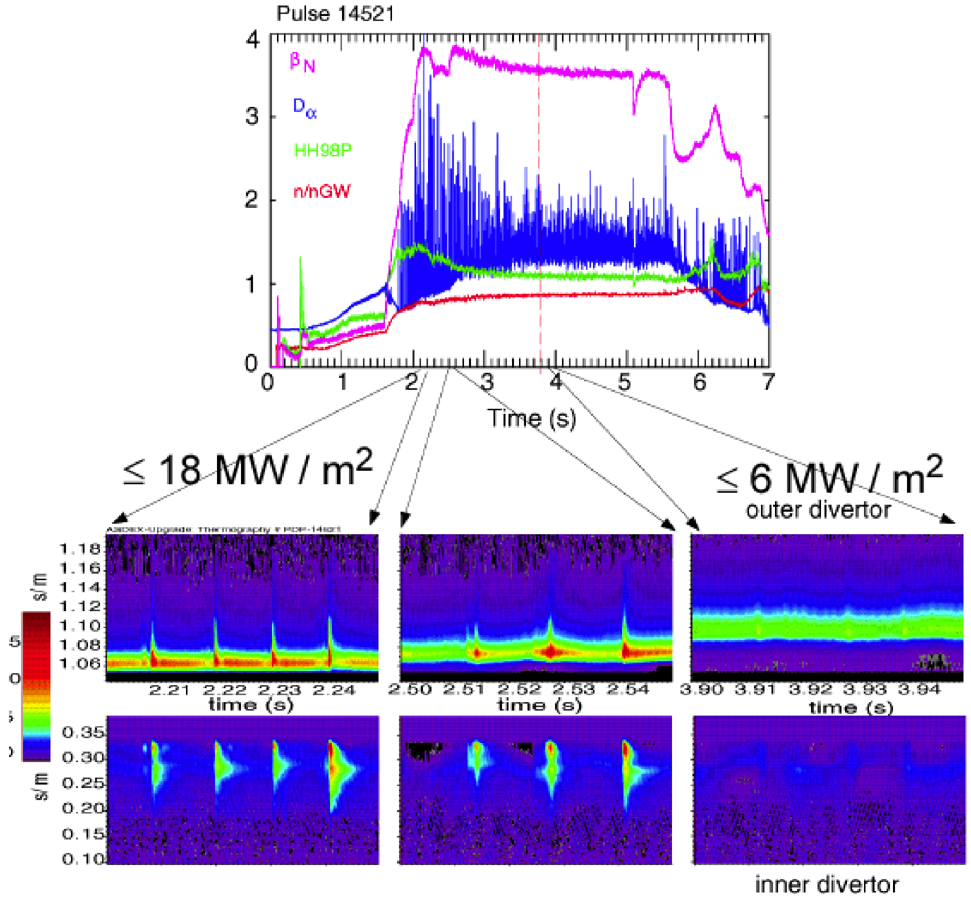


	JET	ITER
$H_{98\,(y,2)}$	0.91	1.0
$\beta_{N,th}$	1.90	1.81
n_e / n_{GW}	1.1	0.85
Z_{eff}	1.5	1.7
P_{rad} / P_{tot}	0.40	0.58
κ, δ	1.74, 0.48	1.84, 0.5
q_{95}	3.2	3.0
τ_{pulse} / τ_E	15	110

JET-operating space

Q =10: divertor issues

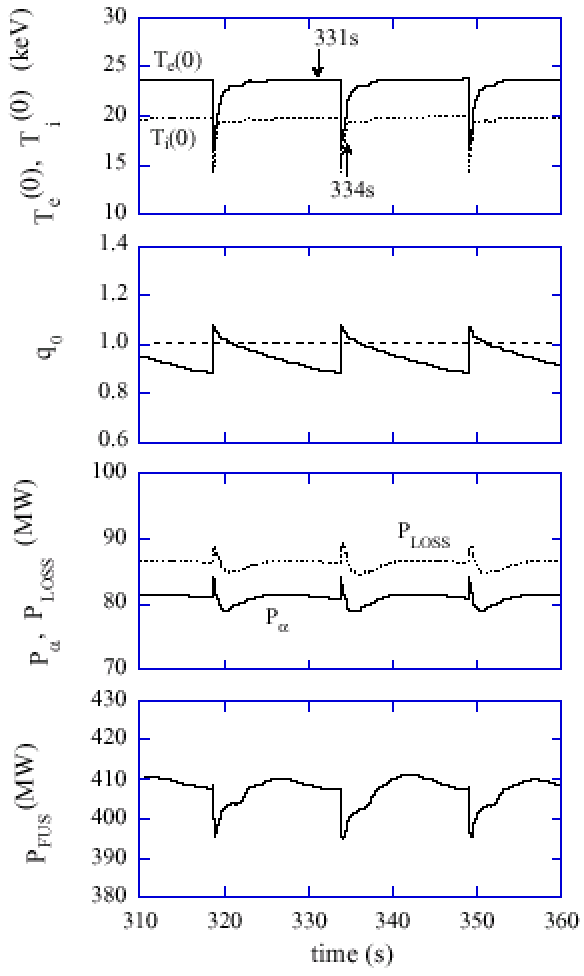
- divertor & plasma wall interaction issues (ELM tolerance, tritium):
  - determine pulses: how long & how often
  - has to be solved for any kind of fusion reactor
  - focussed effort starts bearing fruit
    - type 2 ELMs
    - control of C erosion & tritium co-deposition by surface temperature control
    - viability of W-solution
    - Be-experiments on Pisces



Q =10: a-particle effects

a-particle confinement:

- **classical confinement good** **(ripple reduction through ferromagentic inserts)**
- AE-modes: **for „nominal“ (monotonic) q-profiles (PENN,Mishka):**
    - **linearly stable or**
    - **weak redistribution of a-particles**
- fishbones: **(marginally) unstable for nominal parameters**



sawteeth:

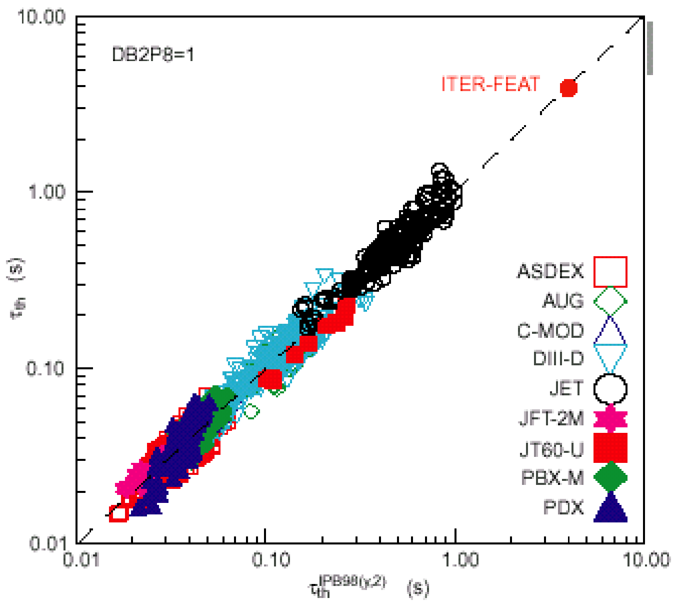
•period extended by a-particle stabilisation

•30% central T-excursion

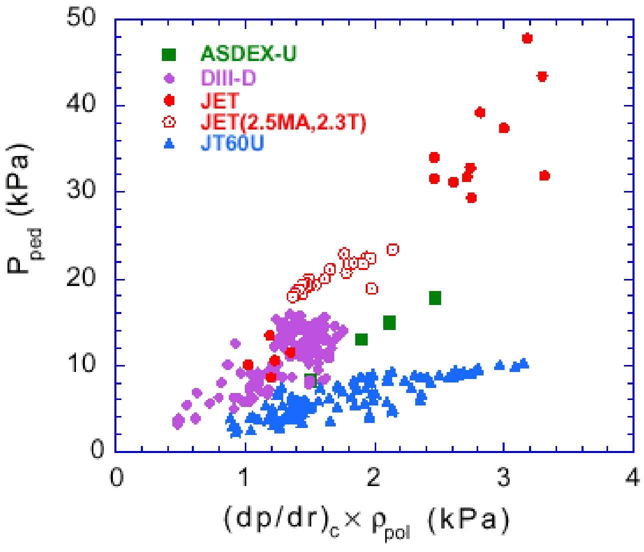
•small effect on heat flux

Extend scaling and verify theory: confinement

- global scaling

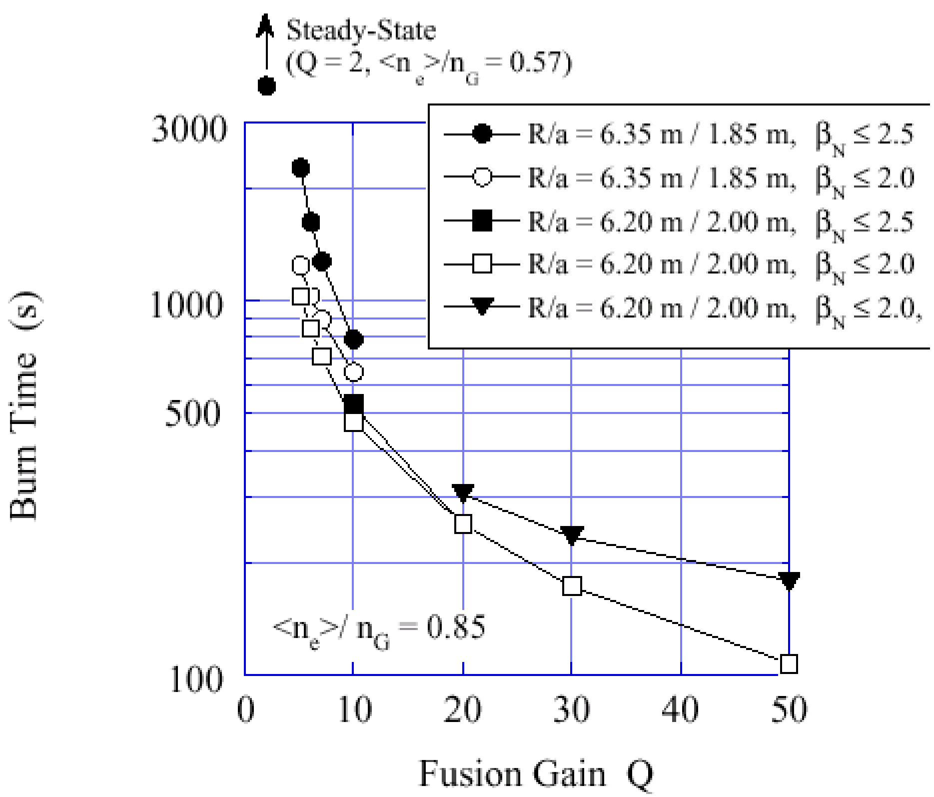


- pedestal scaling
  - pressure gradient limited
  - spatial scale? $R^{\alpha}\rho^{1-\alpha}$



- profile stiffness
  - agreement with codes
  - role of self-generated shear-flows
  - electron transport
- role of n/n_{GR} vs n*

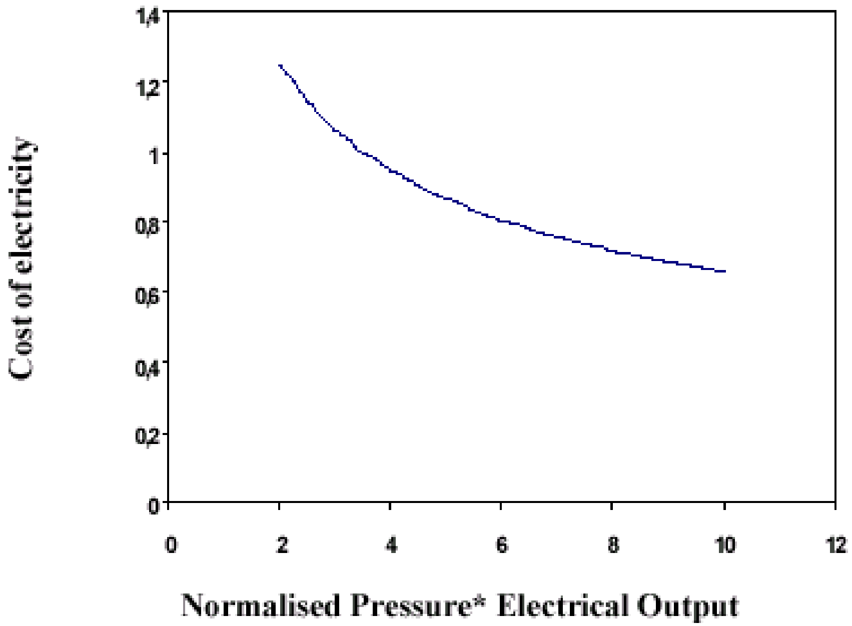
hybrid scenario: conservative scenario for technology testing



	Scenario 3
	Hybrid #1
R (m)/a (m)	6.2/2.0
κ_{95}/δ_{95}	1.7/0.33
V_P (m^3)	831
B_T (T)	5.3
I_P (MA)	13.8
q_{95}	3.3
$<n_e>$ ($10^{19}m^{-3}$)	9.3
$<n_e>/n_G$	0.85
$<T_i>$ (keV)	8.4
$<T_e>$ (keV)	9.6
β_N	1.9
P_{FUS} (MW)	400
P_{NB} (MW)	33
P_{RF} (MW)	40
$Q = P_{FUS}/(P_{NB}+P_{RF})$	5.4
I_{CD}/I_P (%)	25
I_{BS}/I_P (%)	17
γ_{20}^{NB} ($10^{20}AW^{-1}m^{-2}$)	0.24
γ_{20}^{RF} ($10^{20}AW^{-1}m^{-2}$)	0.30
γ_{20}^{TOT} ($10^{20}AW^{-1}m^{-2}$)	0.27
τ_{He}^*/τ_E	5
$H_{H98(y,2)}$	1.0
V_{loop} (mV)	56
Burn flux (Vs)	60
Burn time (s)^{*1}	1070

advanced tokamak operation on ITER

- satisfy „steady-state“ objective
- prepare DEMO (i.e. characteristics of a commercially viable reactor)
  - blue ribbon „fast track“ panel
  - fusion industry committee



- associated physics issues   match ITER capabilities
  - a-physics compatibility
  - long pulse aspects
    - current profile
    - plasma surface interaction
  - 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
$\langle\beta\rangle$ [%]	2.5	2.9	2.2 - 3	3 - 5

steady state („advanced“) scenarios:

- development needed
- spectrum of scenarios
- scenarios illustrative

	Scenario 4		Scenario 6	Scenario 7	
	WNS	WNS	SNS	WPS	Low-Q
R/a (m)	6.35/1.85	6.35/1.85	6.35/1.85	6.35/1.85	6.35/1.85
B_T (T)	5.18	5.18	5.18	5.18	5.18
I_P (MA)	9.0	9.5	9.0	9.0	11.0
κ_{95}/δ_{95}	1.85/0.40	1.87/0.44	1.86/0.41	1.86/0.41	1.84/0.43
$<n_e>$ $(10^{19}m^{-3})$	6.7	7.1	6.5	6.7	5.7
n/n_G	0.82	0.81	0.78	0.82	0.57
$<T_i>$ (keV)	12.5	11.6	12.1	12.5	9.3
$<T_e>$ (keV)	12.3	12.6	13.3	12.1	12.1
β_T (%)	2.77	2.67	2.76	2.75	2.2
β_N	2.95	2.69	2.93	2.92	1.9
β_p	1.49	1.25	1.48	1.47	0.77
P_{fus} (MW)	356	338	340	352	174
$P_{RF} + P_{NB}$ (MW)	29 + 30 *1	35 + 28 *1	40 + 20 *2	29 + 28 *3	36 + 50
$Q = P_{fus}/P_{add}$	6.0	5.36	5.7	6.2	2.0
W_{th} (MJ)	287	292	287	284	212
P_{loss}/P_{L-H}	2.59	2.74	2.63	2.6	3.0
τ_E (s)	3.1	2.92	3.13	3.07	2.15
f_{He} (%)	4.1	4.0	4.0	4.0	3.0
f_{Be} (%)	2	2.0	2	2	2
f_{Ar} (%)	0.26	0.16	0.2	0.23	0.19
Z_{eff}	2.07	1.87	1.89	1.99	1.86
P_{rad} (MW)	37.6	30.6	36.2	34.6	22
P_{loss} (MW)	92.5	100.0	91.6	92.7	99
l_i (3)	0.72	0.43	0.6	0.69	0.58
I_{CD}/I_p (%)	51.9	49.7	53.7	50.2	73.6
I_{bs}/I_p (%)	48.1	50.3	46.3	49.8	26.4
I_{OH}/I_p (%)	0	0	0	0	0
$q_{95}/q_o/q_{min}$	5.3/3.5/2.2	5.0/3.8/2.7	5.4/5.9/2.3	5.3/ 2.7/2.1	4.1/ 1.5/1.3
$H_{H98(y,2)}$	1.57	1.46	1.61	1.56	1.0
τ_{He}^*/τ_E	5.0	5.0	5.0	5.0	5.0

extrapolation and extension of regime

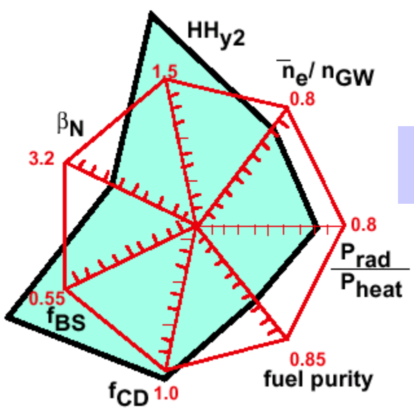
approach to ITER s.s.-targets in dimensionless *performance* parameters:

the 7-fold way*)

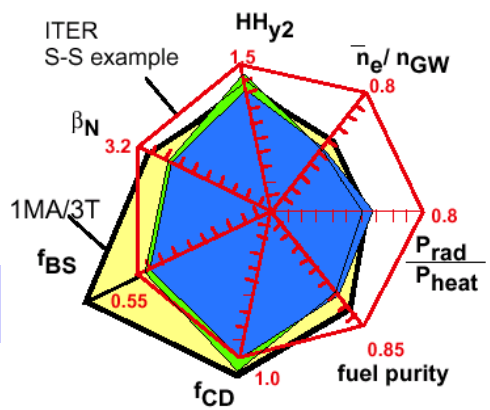
*) + pulse length: -> only full CD,ELMy H-mode cases shown

smaller q (implied by high f_{BS}, low b_N)

JT-60U RS

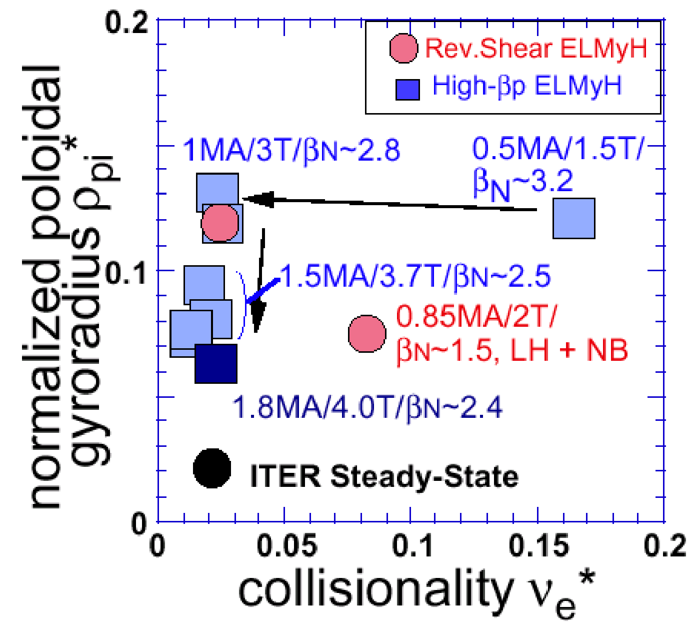


JT-60U high bp



ITER & Power Plant:

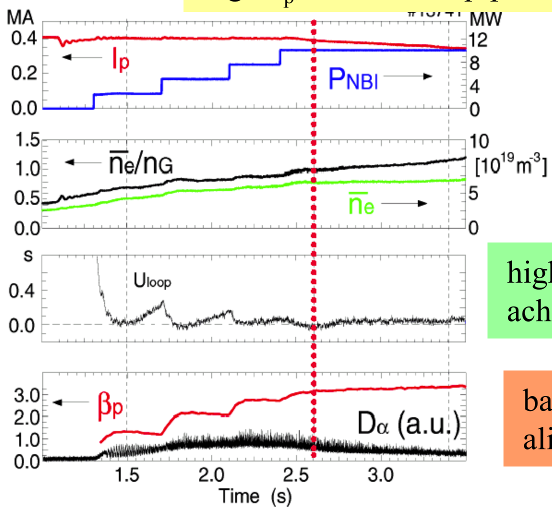
higher n/n_{GW} but lower n* !



self-consistency of parameters and profiles: *a range of „advanced“ regimes exist*

AUG

high b_p, monotonic q- profiles

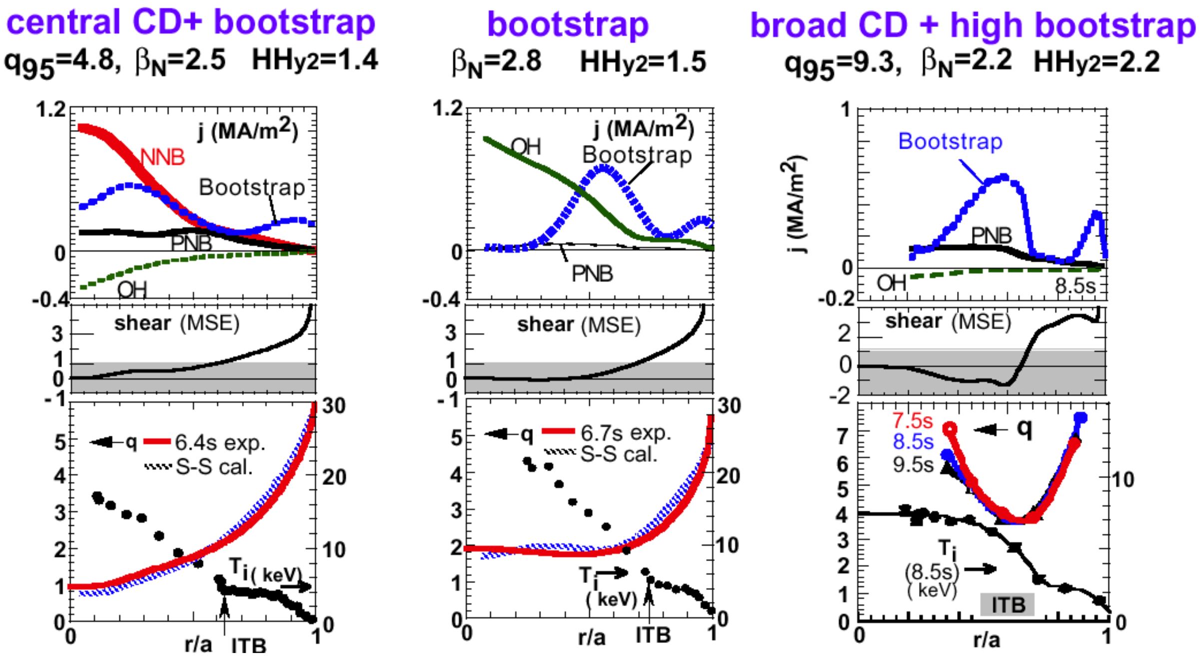


high n/n_{GW} achieved

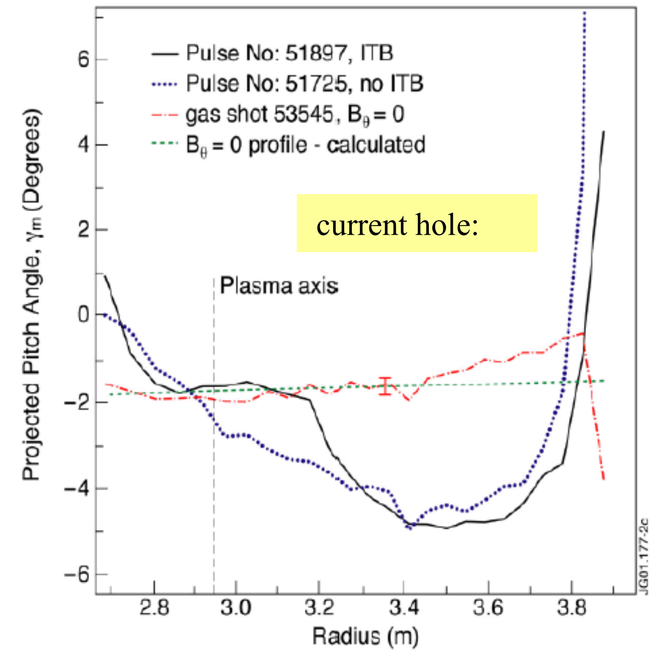
bad bootstrap alignement

good bootstrap alignement

difficult a-particle confinement



JT60-U

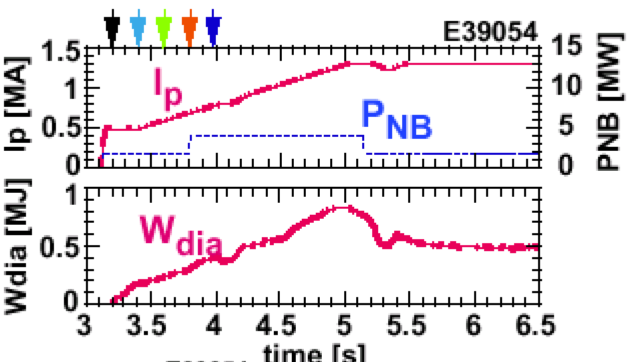


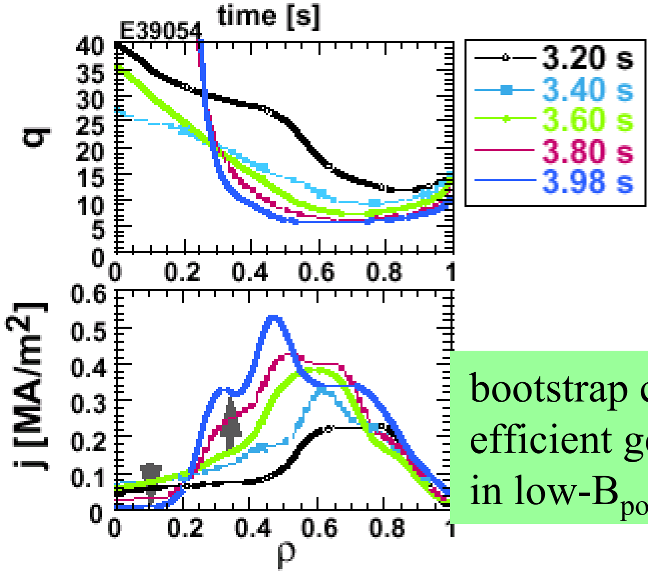
current hole:

JET: LHCD

current holes as extreme of reverse shear

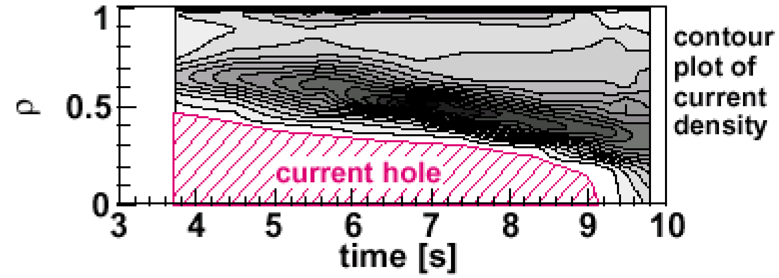
current holes can also be generated exclusively by bootstrap current (JT60-U)

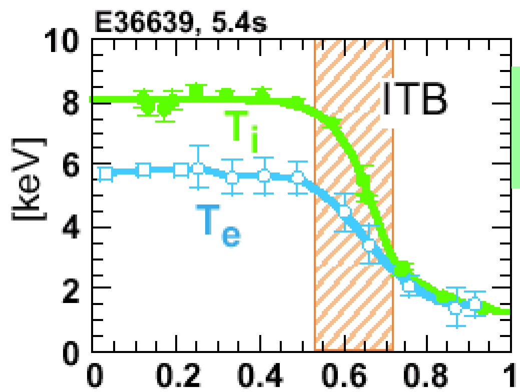




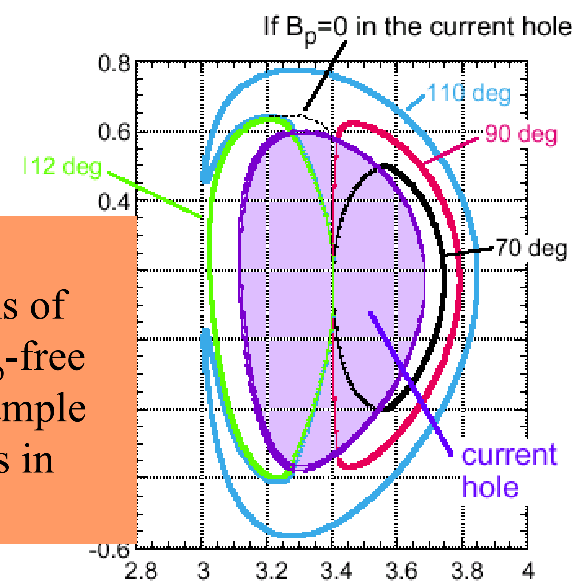
bootstrap current: efficient generation in low-B_{pol}-region

current-distribution stable, decaying only because of residual V_{loop}





high energy density plasma confined by barrier



but large excursions of ions in B_p-free zone (example 4keV ions in JT60-U)

a-particle physics and self-heating in advanced scenarios

significantly more problematic than in standard scenarios

to allow study of instability effects: improve „classical confinement" – ferritic inserts

	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	

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

relevant for D –KAE:

$$\frac{\omega^*}{\omega_{TAE}} \cong 2nq^2\rho^{*2}\left(R\omega_{pi}/c\right)$$

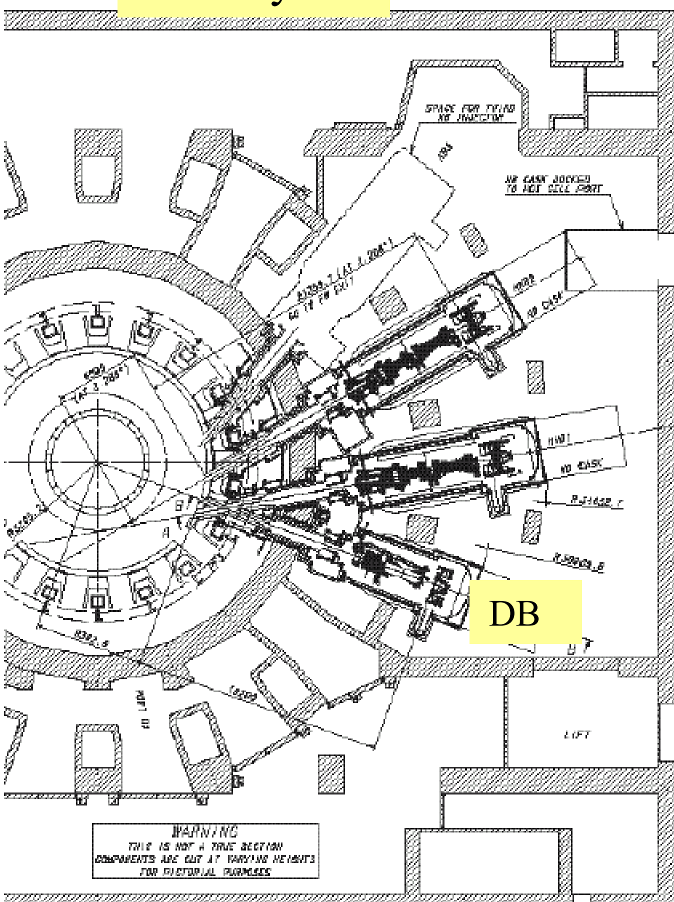
„synergies" between AE core losses and ripple edge losses?

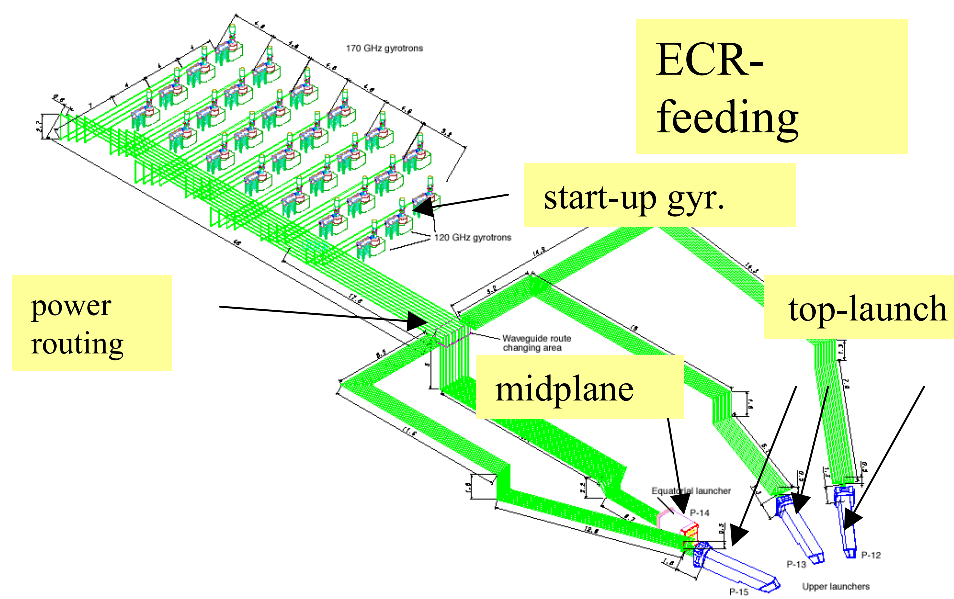
heating & current drive systems

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

heating system	stage I	possible upgrade by	remarks
NBI (1MeV negative ion)	33	16.5*)	vertically steerable (z at R_{tan}: -0.42m to +0.16m)
ECR H&CD (170 GHz) (+2MW 120 GHz for start-up)	20	20	equatorial port & upper port launcher; steerable
ICR H&CD (40 – 60 MHz)	20		$2\Omega_T$ (50% power to ions), $\Omega 3_{He}$ (70% to ions); FWCD
LH H&CD (5GHz)		20	$1.8 < n_{//} < 2.2$
total	73	130 (110 simultan.)	upgrade in different RF combinations possible
ECRH start-up system (120 GHz)	2		
Diagnostic Beam (100 keV H, neg. ion?)	>2		

NBI-layout





heating & current drive systems

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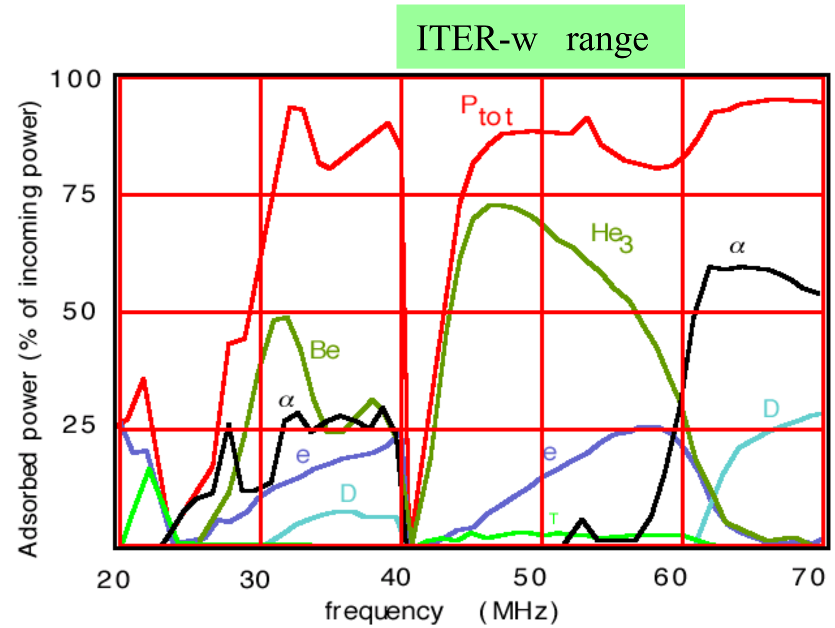
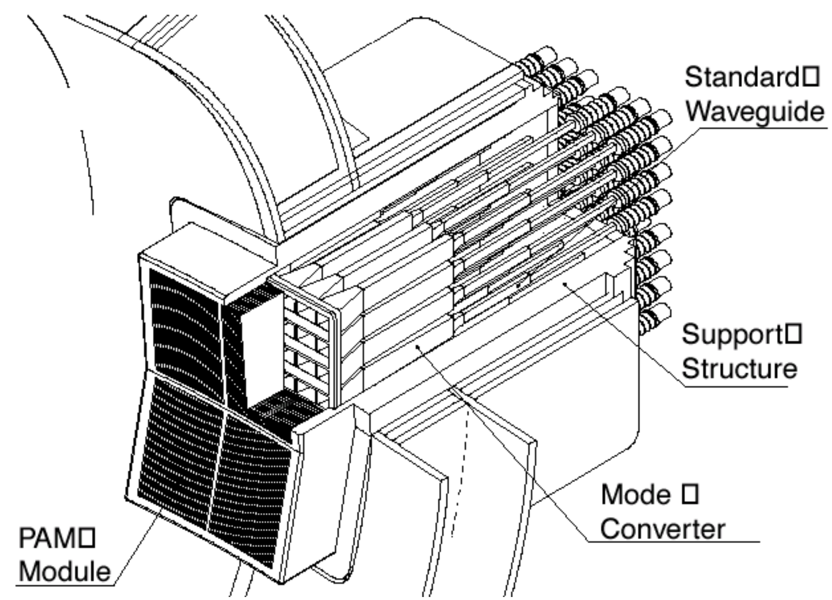


IC power absorbtion by species

LH-launcher; based on Passive-Active Multi-junction principle*)

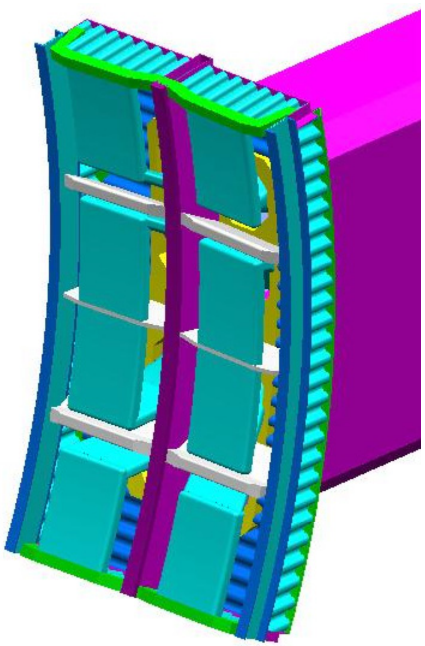
*) to be tested on FTU, Tore-S.



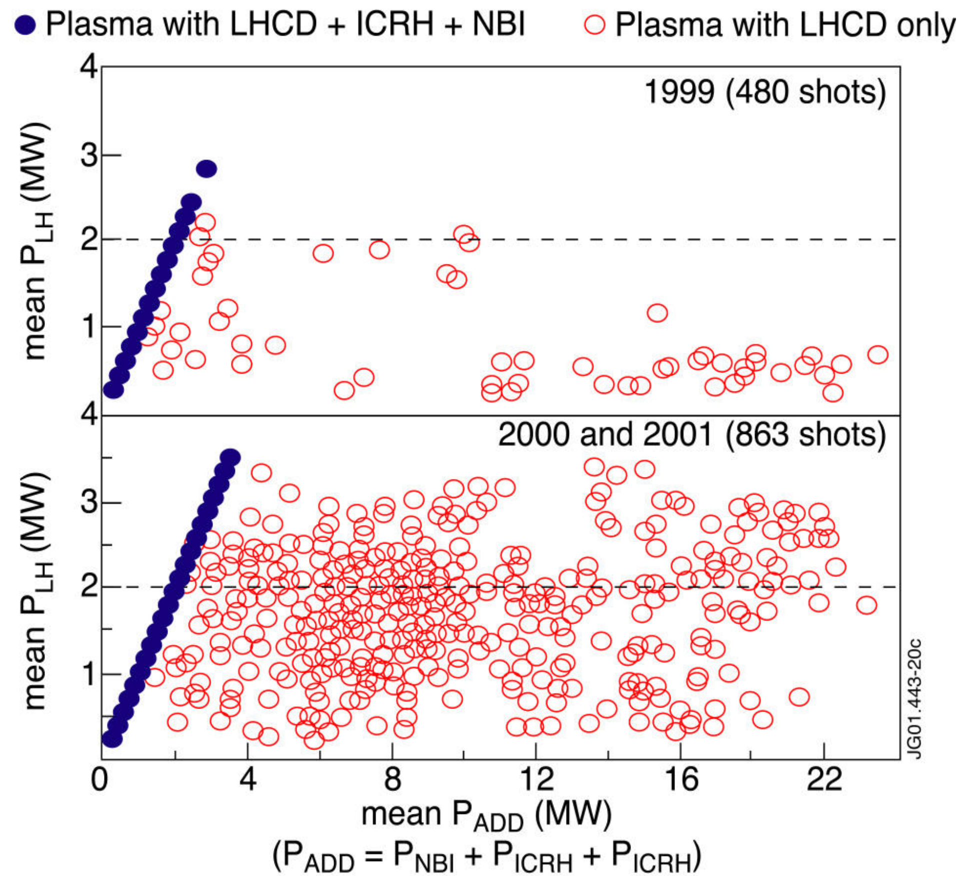
preparatory physics R&D for ITER heating in JET

the JET ICRH ITER-like antenna (2005)

- 7.5 MW at ITER relevant coupling (2-4 W/m)
- High coupling efficiency (90%) in range 30<f<55 MHz
- ELM resilient



strong effort to increase LH availabilty *in combination with other heating systems*



high field side pellet launch

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

inward shift of mass deposition with respect to ablation

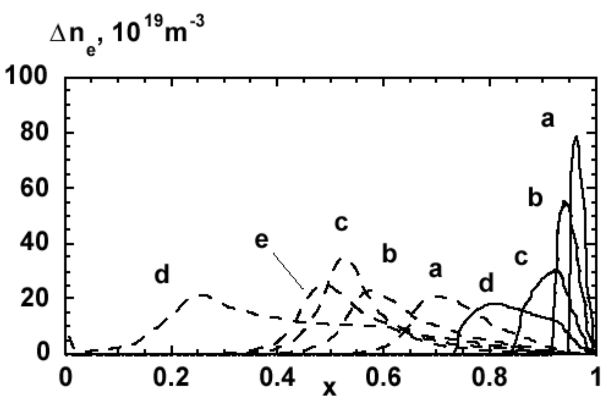
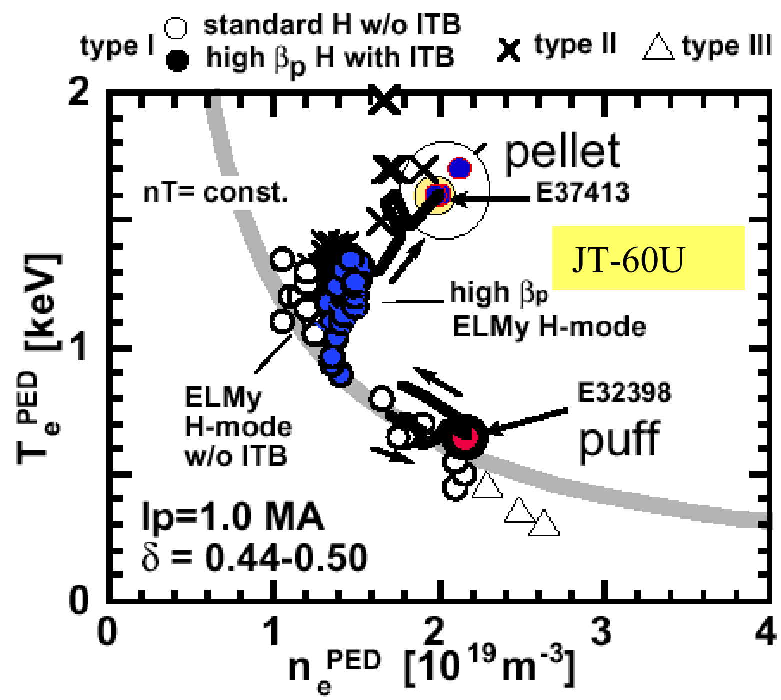


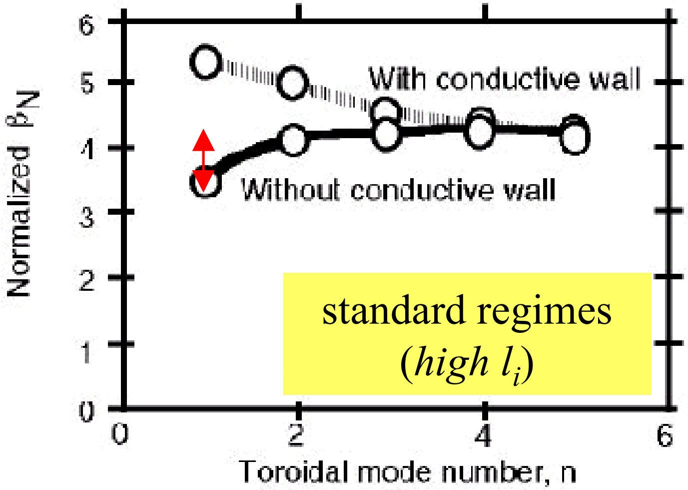
Figure 4.5-2 Model Predictions for the HFS Injection in ITER
Solid lines correspond to pellet ablation, dashed lines for the ablated mass deposition

benefit for high-bp ELMy H-mode

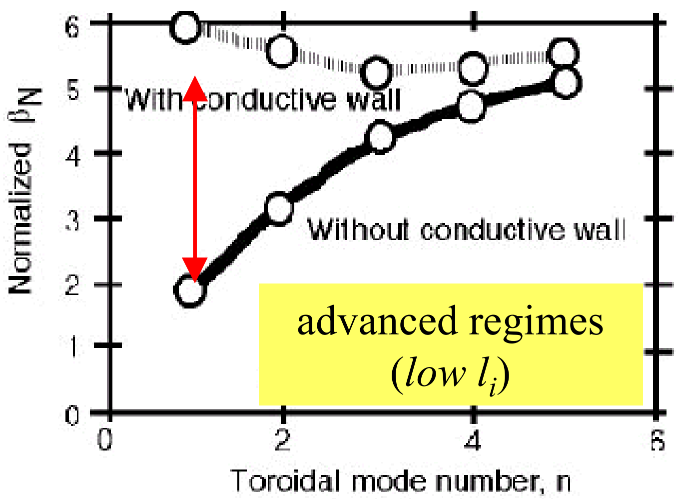


benefit of pellet injection on reverse shear modes: still to be explored

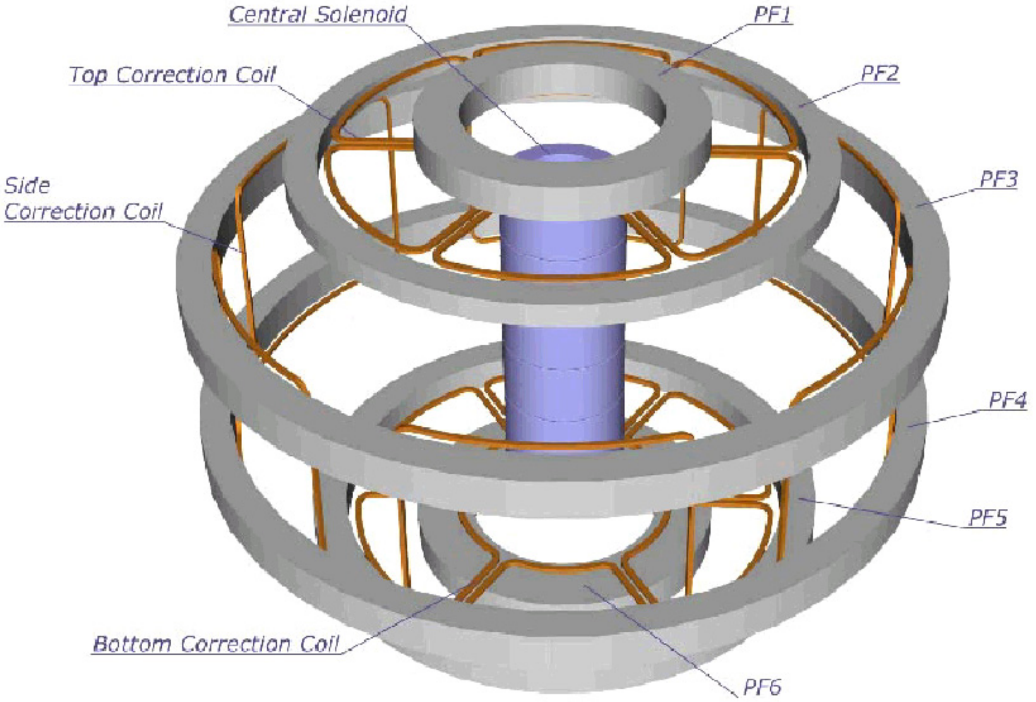
advanced scenarios at high b_n require RW feedback stabilisation



standard regimes
(*high* l_i)



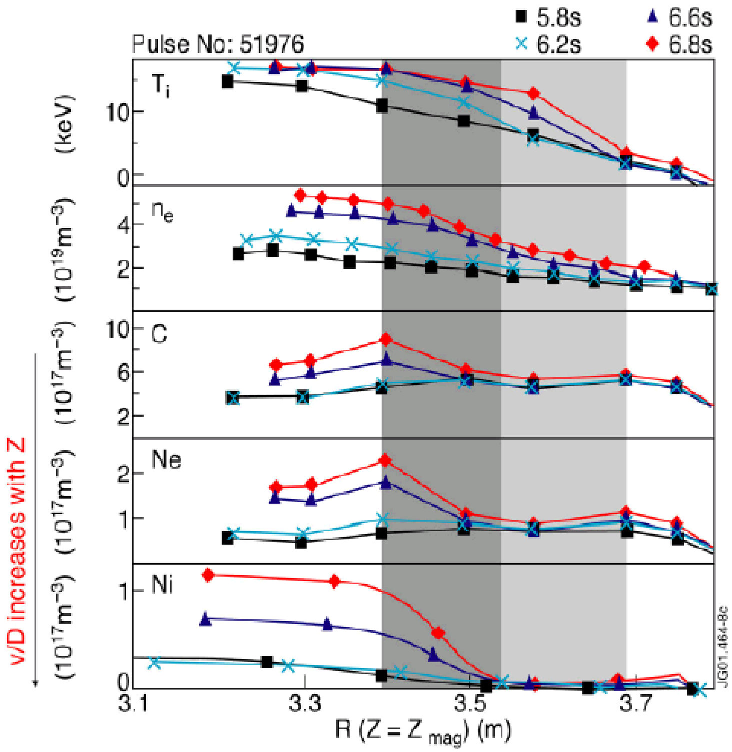
advanced regimes
(*low* l_i)



ITER error field correction and RWM control coils

potential gain by low-n RWM feedback

divertor compatibility and impurity control

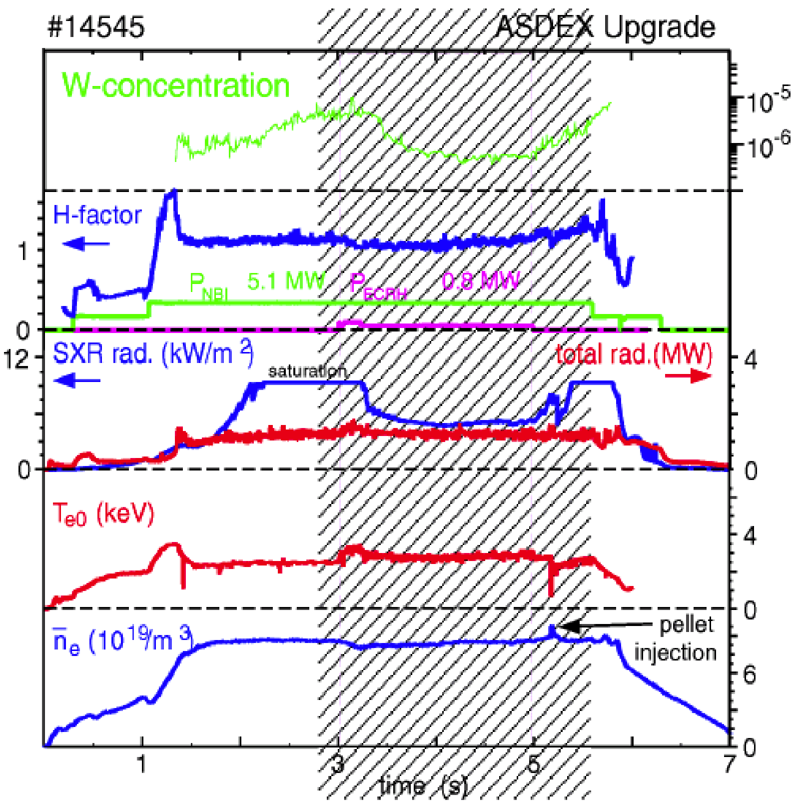


Impurity density development in ITB discharges on JET (similar on JT-60U):

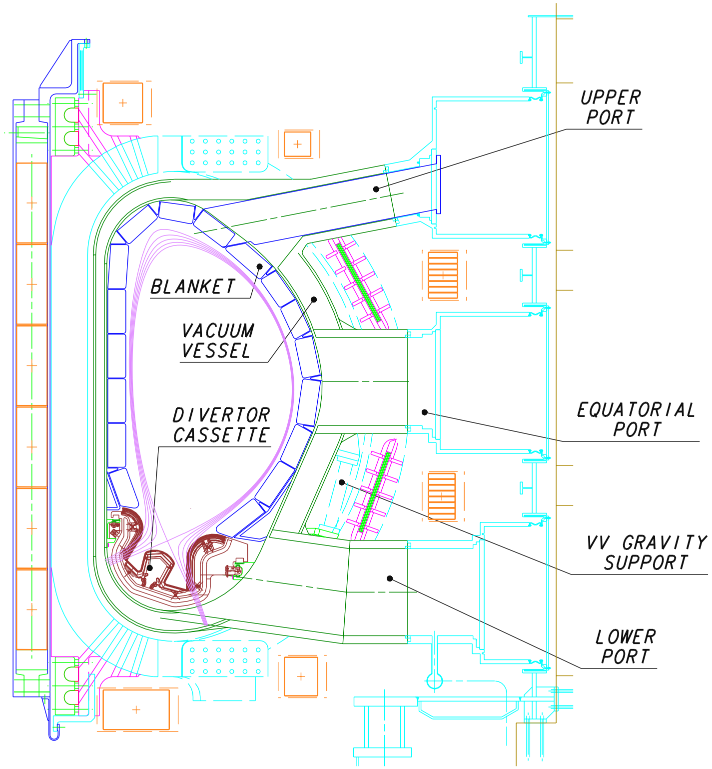
- no accumulation low and med. Z
- accumulation of high-Z

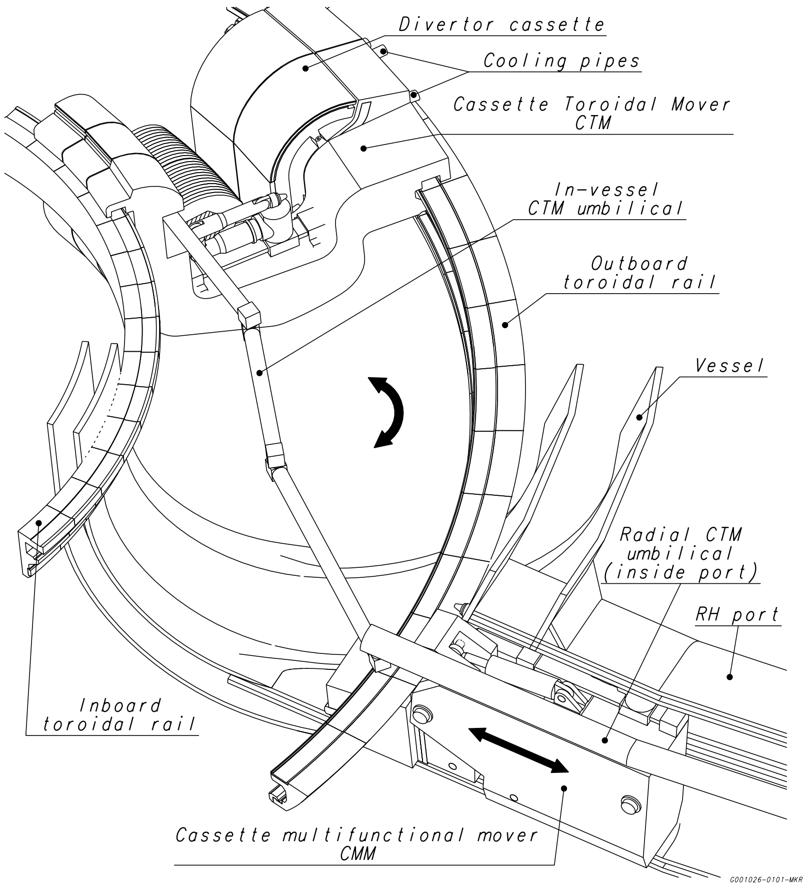
W-experience on AUG:

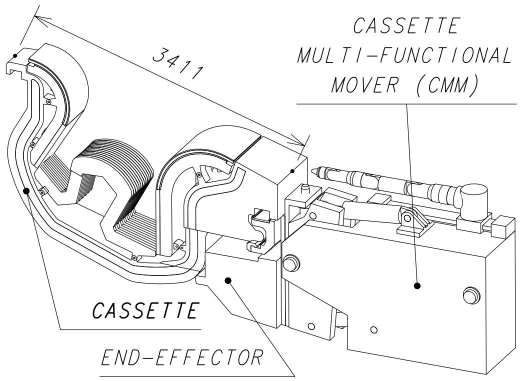
- central (electron) heating suppresses acumulation : *a - heating!*



flexibility through divertor maintanance and exchange capability







for refurbishment and design-improvements

divertor casette system allows replacement of divertor within 6 months:

relevant & attractive range of plasma shapes covered:

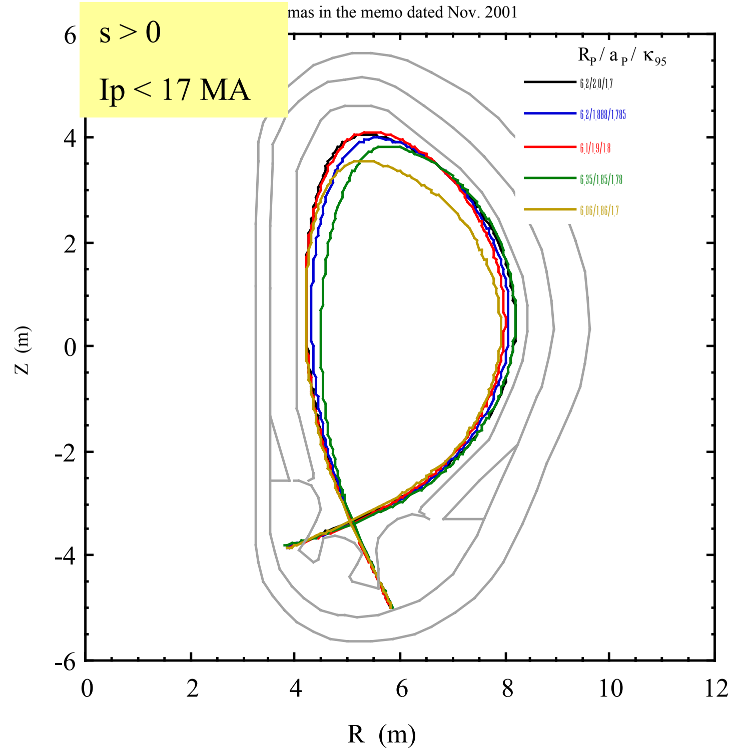
enhanced shaping viz. ITER-FDR

	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

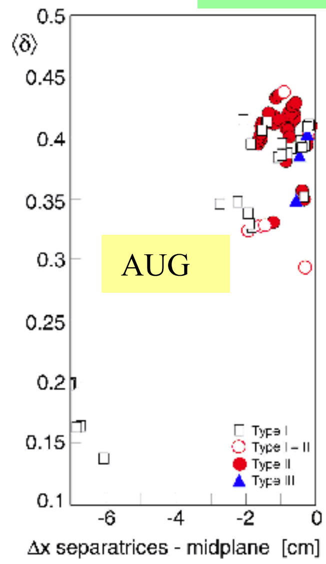
can be further pushed to accomodate important observations

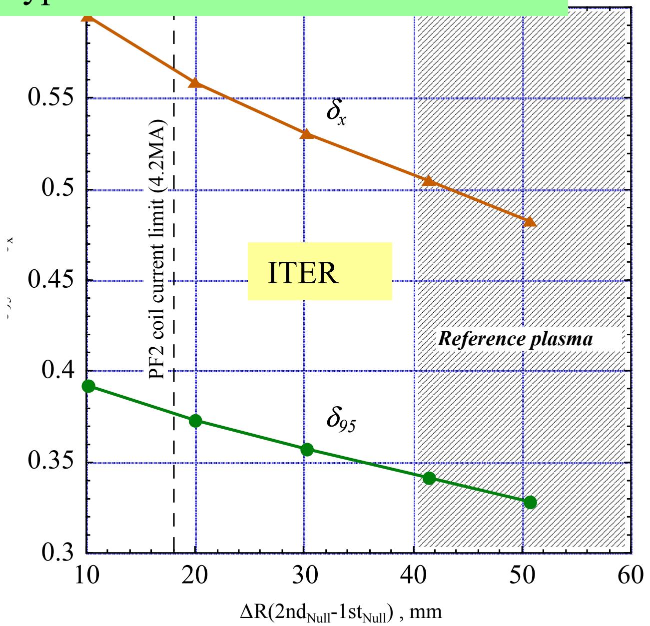
s > 0

Ip < 17 MA



Double-Null proximity (+triangularity)for acces to type II ELMs





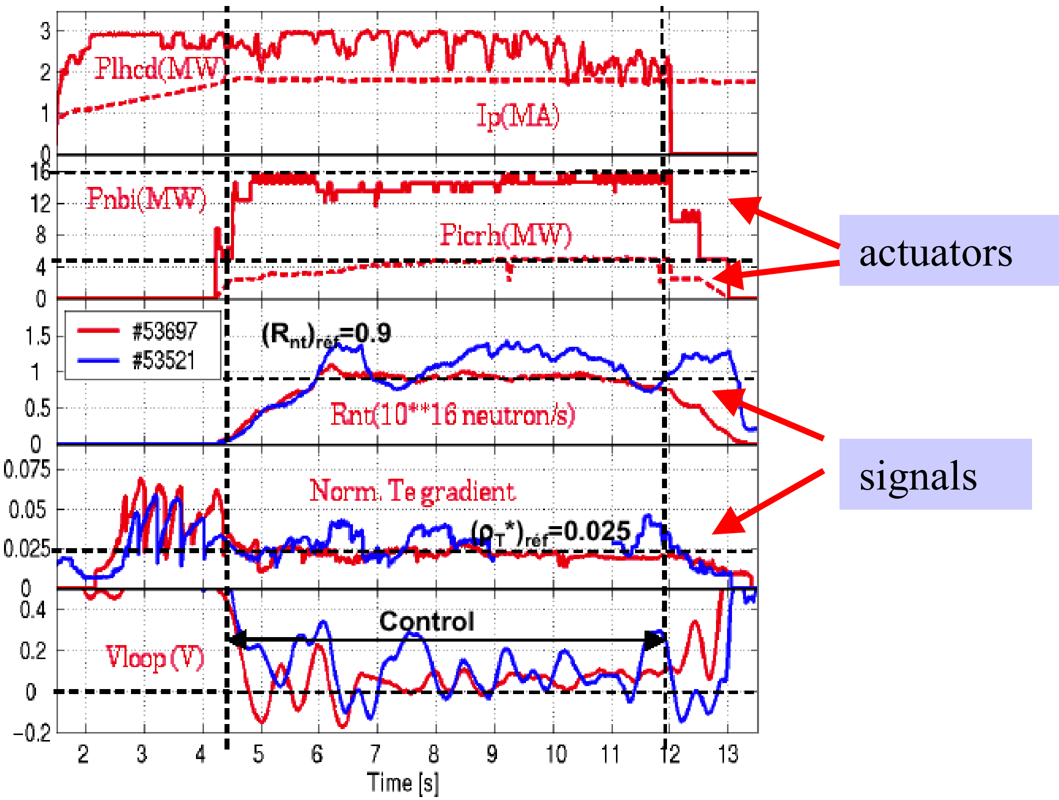
advanced scenarioes - > stronger shaping possible (I_p = 9 MA)

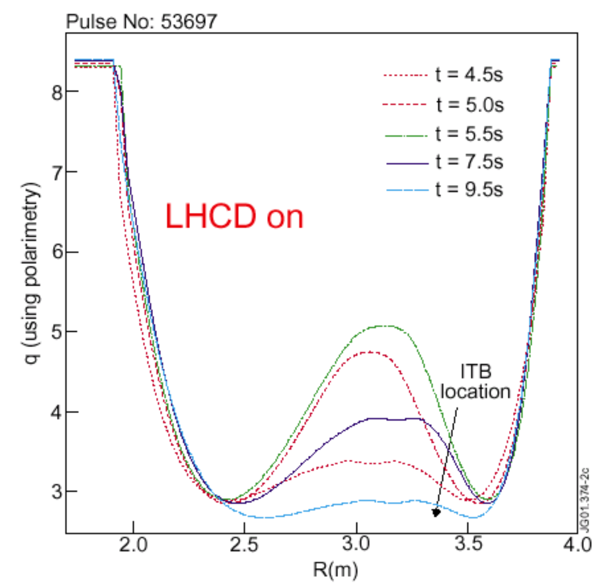
l_i	0.6	0.4
$k_{95,\ ma}$	<2	<2.1

controllability:

long pulse feedback control of JET ITB discharges

LHCD used to delay current profile development





ITB existence criterium and control parameter $\rho_T* = \rho_s / L_T > \rho_{ITB}*$

pulse length & duty cycle

scenario	burn time*) [sec]
inductive, (reference)	500
hybrid	1000
steady-state	3000**)

*) repetition time = 4 x burn time

**) (at present) limited by external cooling capacity

- high availability:

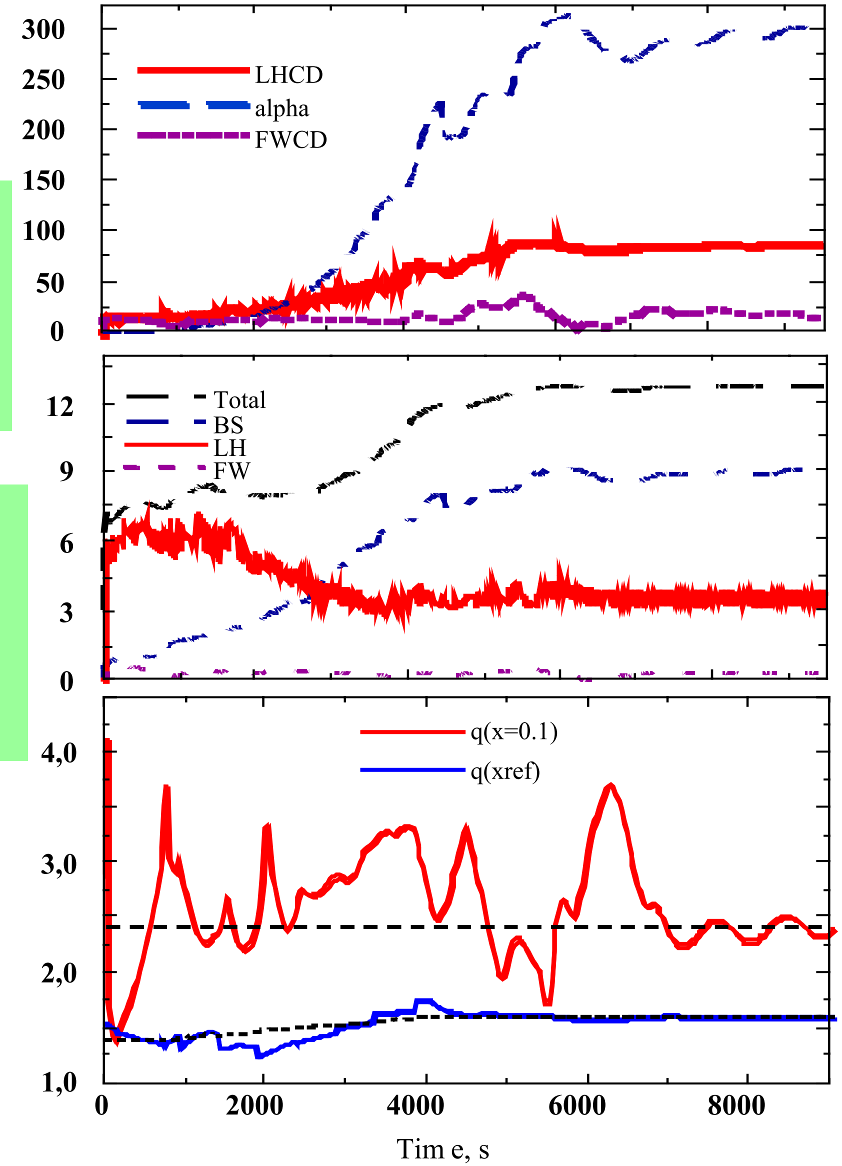
  ⇨ ample time & opportunity for experiments

- (although observation of current diffusion on t ~ t_{skin})

  execution of control:

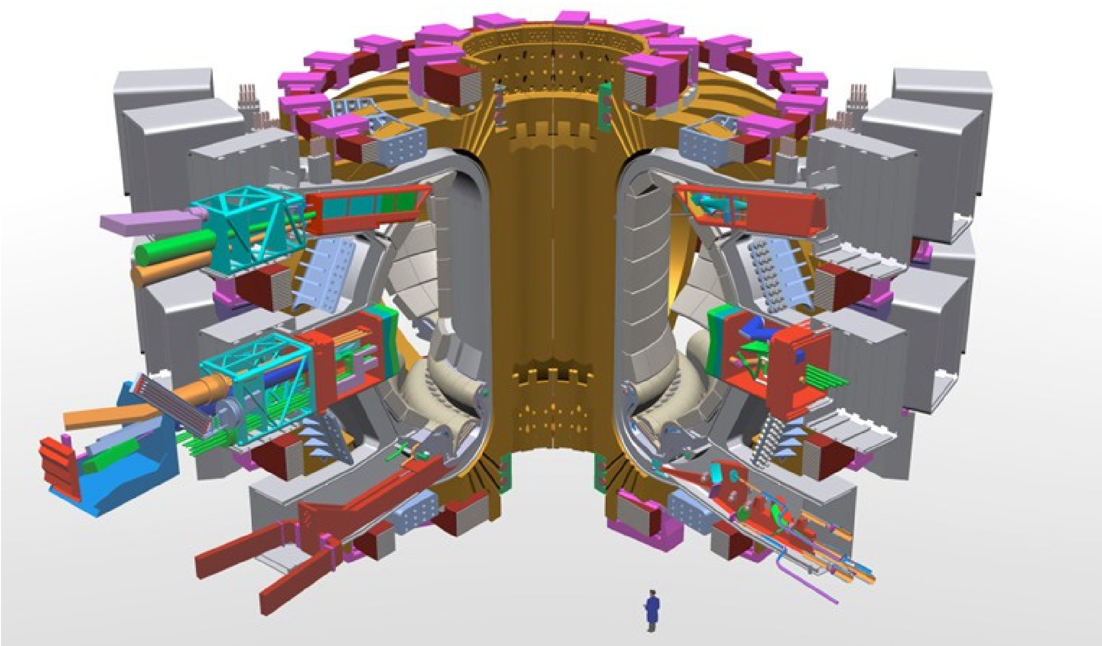
  ⇨ t>>t_{skin}

Moreau: simulation of ITER-FDR *) feedback control with fuelling, FWCD & LHCD

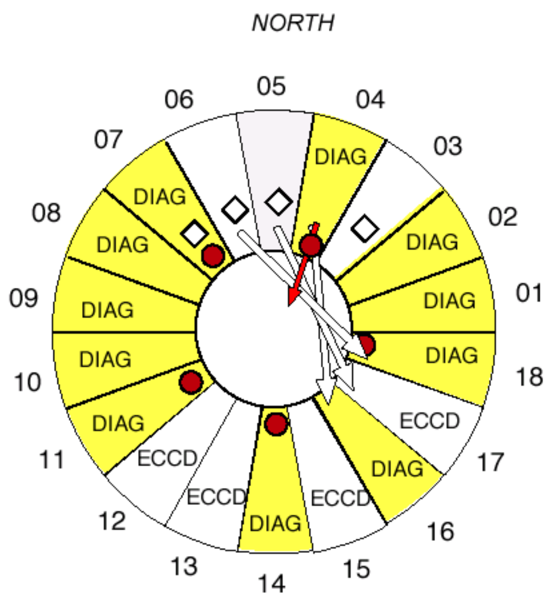


*) reduce times by factor of 2 for ITER-FEAT

diagnostic access & facilities



ITER *UPPER PORT*



1 Active Spectr (MSE)
Neutron Act syst (^{16}N)

2 H-alpha /Visspec(inner edge)
Main plasma reflect.

3 Neutron Camera ◇

4 CXRS(pol rotn - DNB)
Wide angle viewing/IR

5 Neutron Camera ◇
Neutron Act syst (^{16}N)

6 Neutron Camera ◇
Neutron Act syst (foil)

7 Neutron camera ◇
Wide angle viewing/IR

8 Bolometry
Position Reflectometry

9 H-alpha/Vis. spec (upper edge)

10 VUV,
X-ray Crys Array
Neutron Act syst (foil)

11 Edge Thomson scattering
Wide angle viewing/IR

14 Wide angle viewing/IR
Position Reflectometry

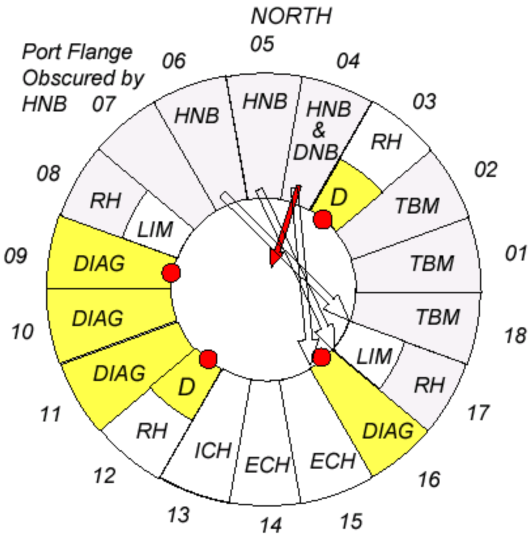
16 Bolometry
Soft X-Ray
Divertor Impurity (div16)

18 Wide angle viewing/IR
H-alpha/Vis. spec (outer edge)

all In-vessel diagnostic wiring

diagnostic access & facilities

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

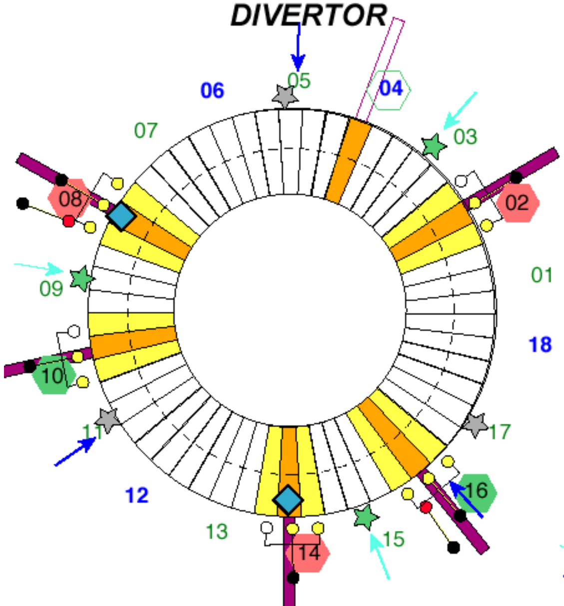
12 Wide angle viewing/IR
H-□ /Vis. spec (upper edge)
Vis. continuum array

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

DIVERTOR



2 VUV Impurity Monitor (g)
IR Thermography (c)
Langmuir Probes
Magnetics Thermocouples

4 CXRS(c)
Dust measurement(g),
Magnetics

8 Reflectometry/Interferometry(g)
LIF (c)
Bolometry , Magnetics
Pressure Gauges

Port
Div. RH large ports
RH-like diag. ports

GDC & IVV (L) plugs
IVV (L)
Gas (GIS) &
Pellet (PIS) (tubes)

10 X-point LIDAR (c)
Div Thomson Scattering (g)
Bolometry, Magnetics
Langmuir Probes
Pressure Gauges,

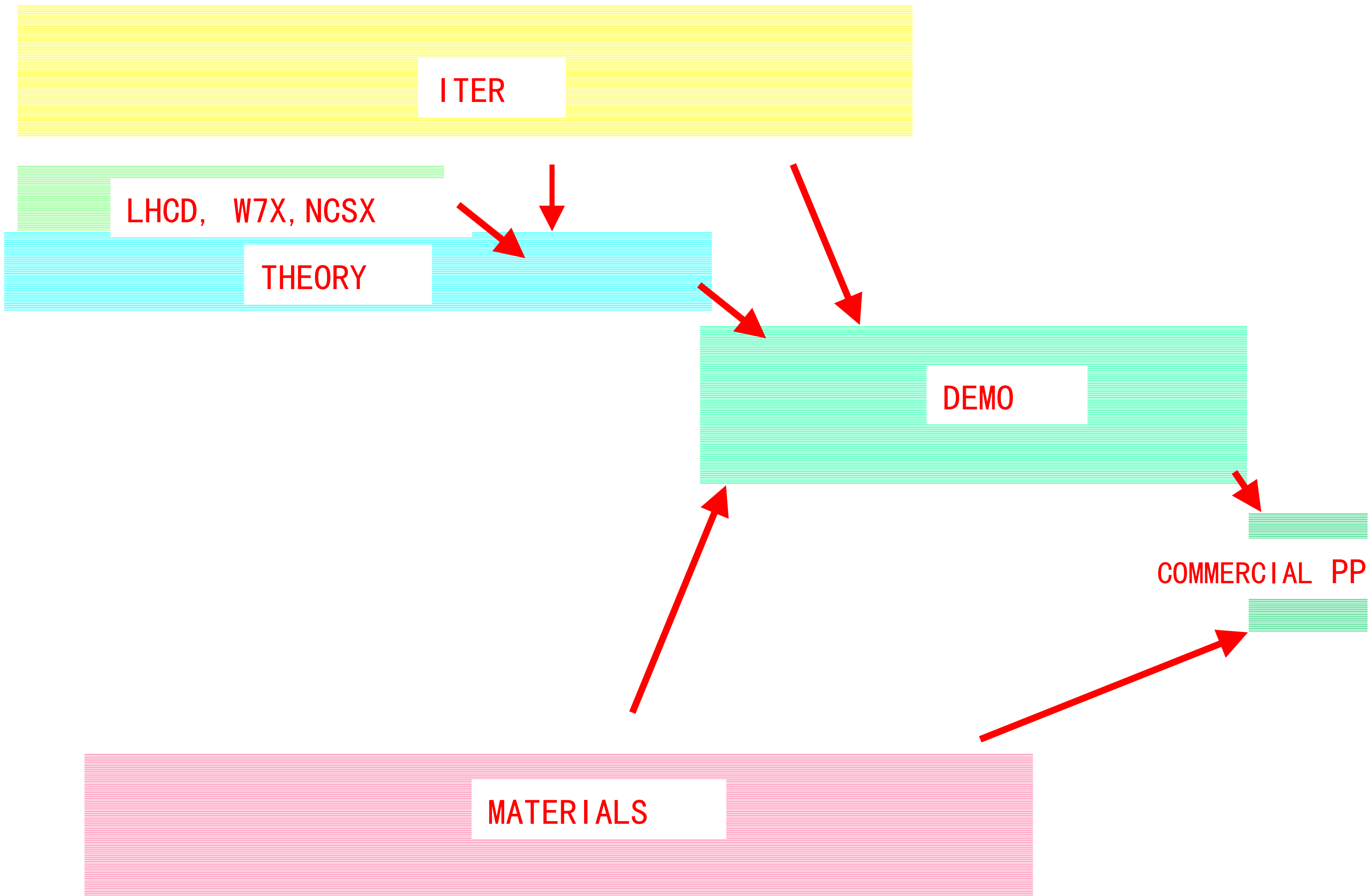
14 Reflectometry/Interferometry (g)
Plate Erosion (c)
Magnetics, Thermocouples
Langmuir Probes

16 Visible Div Impurity Monitor (c,g)
Bolometry, Magnetics
Pressure Gauges,
Thermocouples

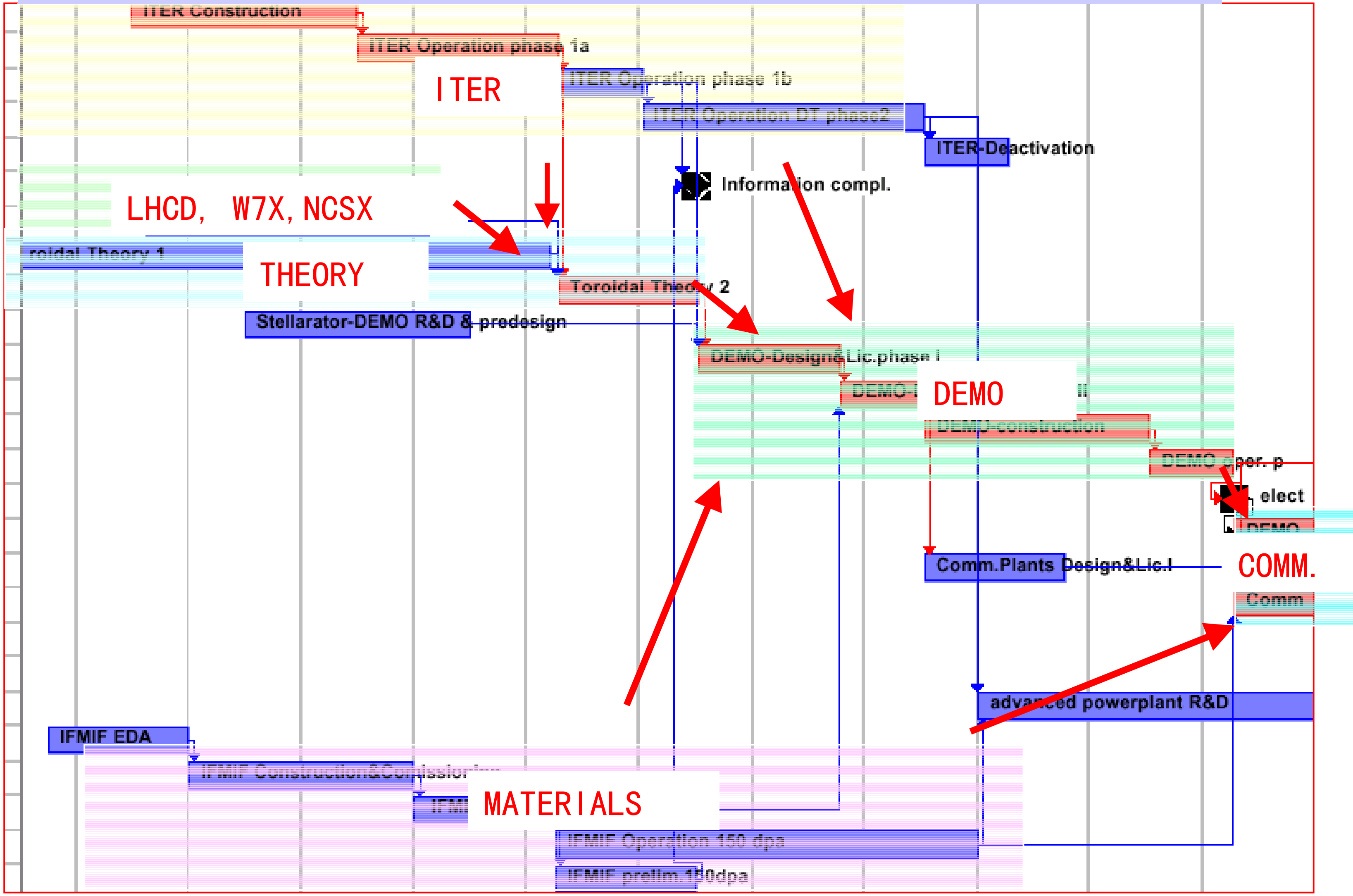
Alloc 7-5-02

ITER´s role for alternatives (e.g.stellarator):

- understand physics of a-particle heating,
- develop PSI solutions
- ...



ITER´s role for alternatives (e.g.stellarator)



Summary

ITER: possibly different role in fusion strategy of EU,Japan&Russia and USA

public and political attitude towards fusion R&D in Europe

exemplified by hearing in German parliament: questions (and answers by IPP, FZJ,FZK) in English translation http://EFDA.ipp.mpg.de/portal/add_info/debates.htm->Hearing on Nuclear Fusion / engl.

composition:

Status of Fusion Physics	Status of Fusion Technology	Environment, Safety and Proliferation	Costs and Financing of Fusion Research	Fusion role in Energy Systems
8	10	24	34	12

examples:

C.1. What steps with what estimated costs in what period must be taken until an economically usable fusion reactor will be available.

C.4. What have been the costs of total fusion research up to the present?

C.5. What have been the costs of preparing for the ITER project since 1985 ?How much is publicly financed and how much comes from industry ?

C.6. How high are the costs estimated for a first test reactor, a later planned second test reactor and the further development steps up to first commercial electricity production ?

C.7. Can the costs of approx. DM 150 billion including over DM 50 billion estimated to arise in the EU specified in the recent TA study"Advanced Nuclear Systems" by the Swiss Science Council for the ITER path be confirmed ?

Summary

to fullfill ITER´s missions

ITER must carry out an extensive and ambitious physics programme

its essential design features give it also capability to do this

- pulse length and duty cycle
- diagnostic access & facilities
- flexible heating, current drive system
  - total power
  - composition
- other plasma engineering systems
  - inside pellet launch
  - RWM feedback
- divertor exchange capability
- shape flexibility

ITER operating scenarios

- **base-line: high confidence**
- **advanced: good prospects, broad spectrum, exciting physics**

EU-tokamak programme (in coll. with Japan & US)

proves compatibility between ITER relevance & programmatic width

- solve H->10 critical issues
  - n/nGR ->1
  - NTMs
- identify approaches to physics/technology interface issues
  - ELMs, tritium inventory
- prepare steady-state/advanced operating scenarios