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SMR 1521/18

AUTUMN COLLEGE ON PLASMA PHYSICS

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ITER

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ITER and the mid & long term physics fusion program

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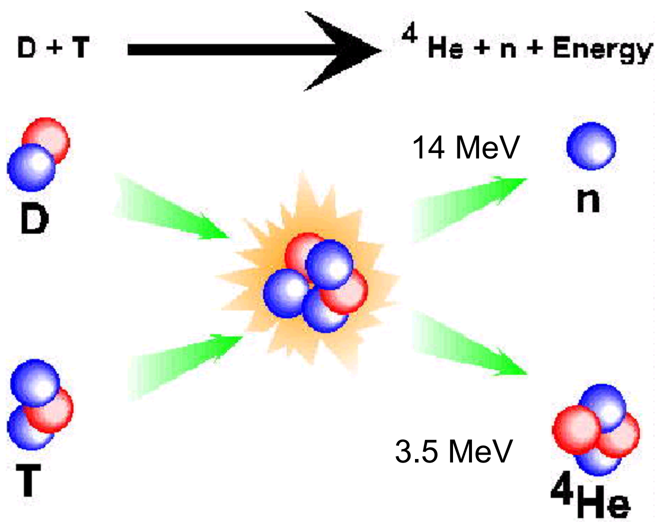
- why fusion
- ITER
  - role in fusion development strategy
  - ITER as a physics experiments
- fusion physics beyond ITER
  - requirements of a power plant
  - the stellarator alternative

acknowledgements to D. Campbell, S. Günter, W.Suttrop, ASDEX Upgrade Team

Fusion Basics: steady state magnetic confinement fusion: fusion is a „burn“ process, with a burn temperature of > 100 Million ° K

DT Fusion Reaction & Fuel Cycle

D-T Fusion Reaction



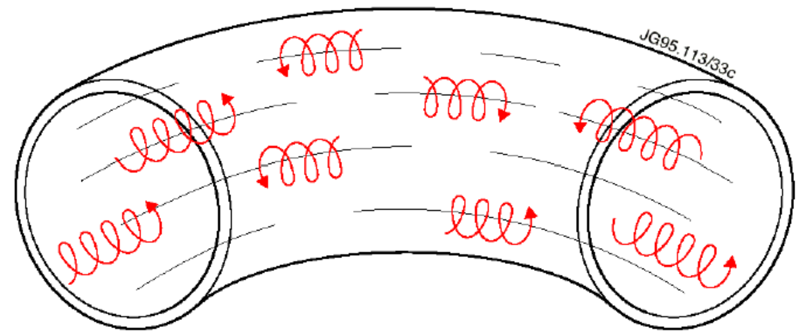
neutrons recycled for T-production

$^6Li + n \rightarrow He + T + 4.8\ MeV$

$^7Li + n \rightarrow He + T + n\ - 2.5\ MeV$

$$Q = \frac{\text{fusion power produced}}{\text{external heating power applied}}$$

principle of toroidal magnetic confinement



magnetic field reduces drastically perpenticular mobility of particles

balances the plasma pressure (O(10atm))

produces thermal insulation (200 Million K)

$$\beta = \frac{k\langle n_e T_e + n_i T \rangle}{B^2 / 2\mu_o}$$

$$\tau_E = \frac{\frac{3}{2} k\langle n_e T_e + n_i T \rangle V_p}{P_{heat}} = H \cdot \tau_{E,scaling}$$

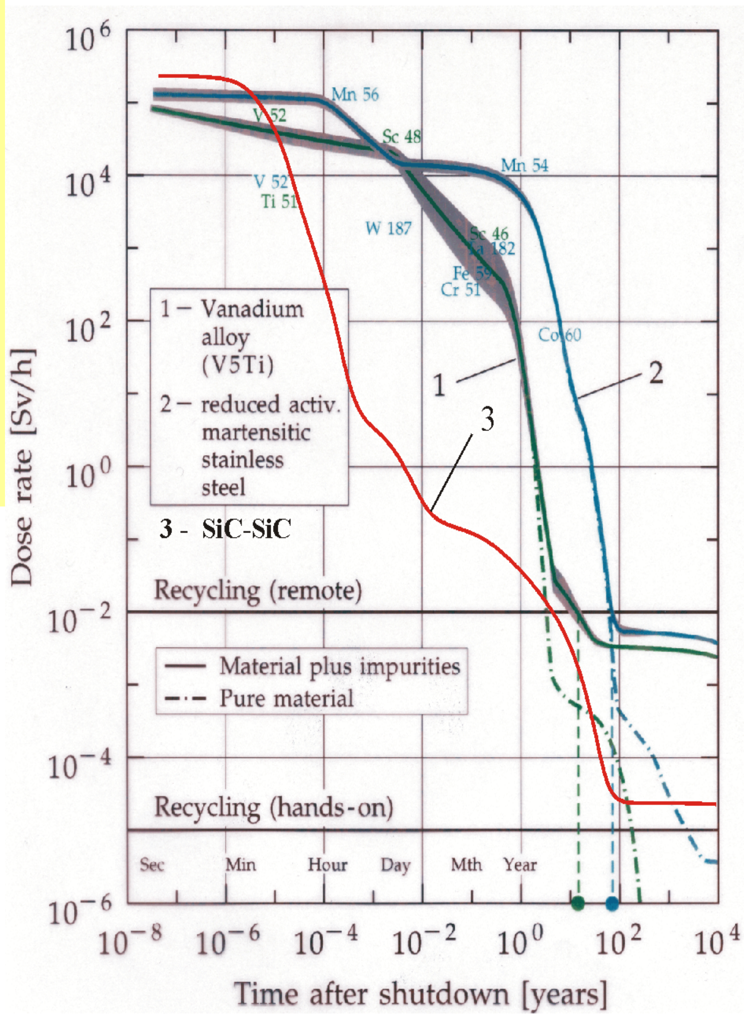
Fusion Basics: intrinsic properties of magnetic fusion

pro:

- abundant, distributed fuel
- fuel cycle closed on site (tritium breeding and burnup)
- safety: low afterheat, fuel inventory for 1´burn, no chain reaction but thermal burn process
- waste only activated structural and functional material: large potential for minimization

con:

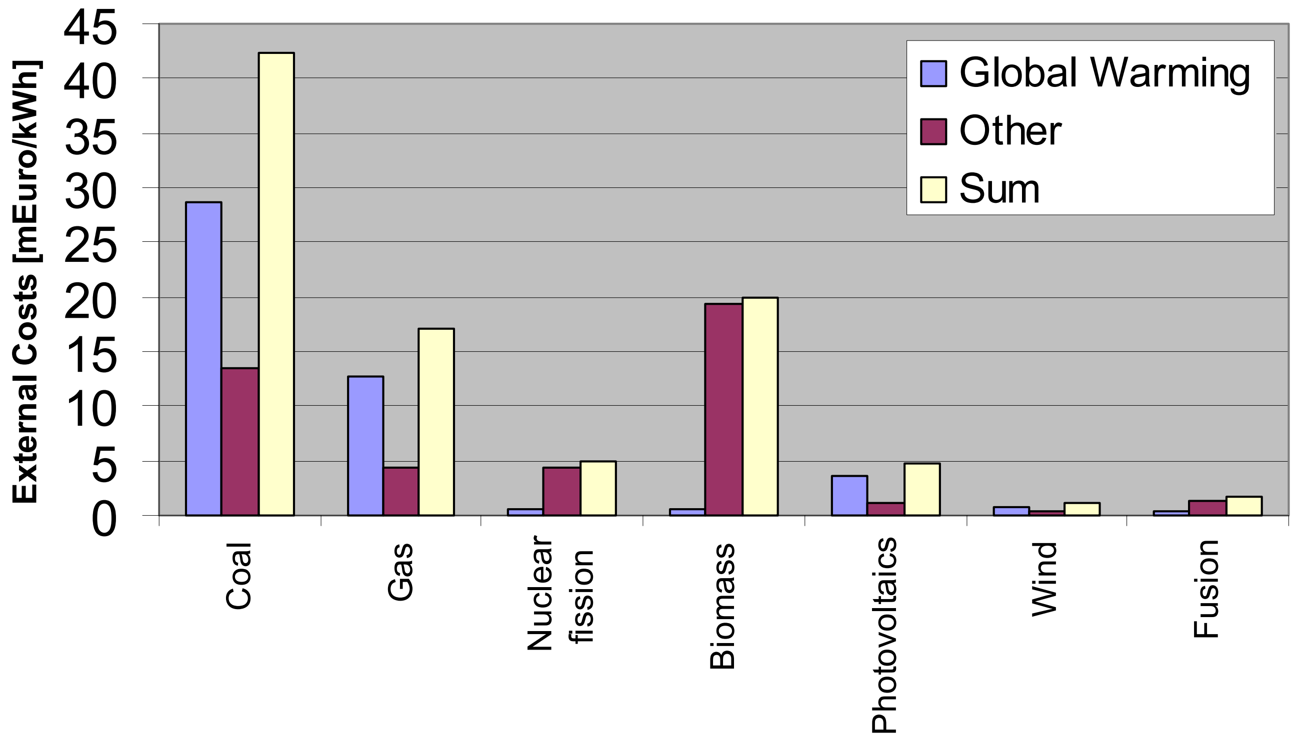
- difficult to initiate and maintain: >100 Mill. K, high energy confinement time, plasma pressure
- complex technology: magnets, remote handling, fuel cycle, power fluxes
- tritium handling



potential role of fusion: environmental impact of fusion

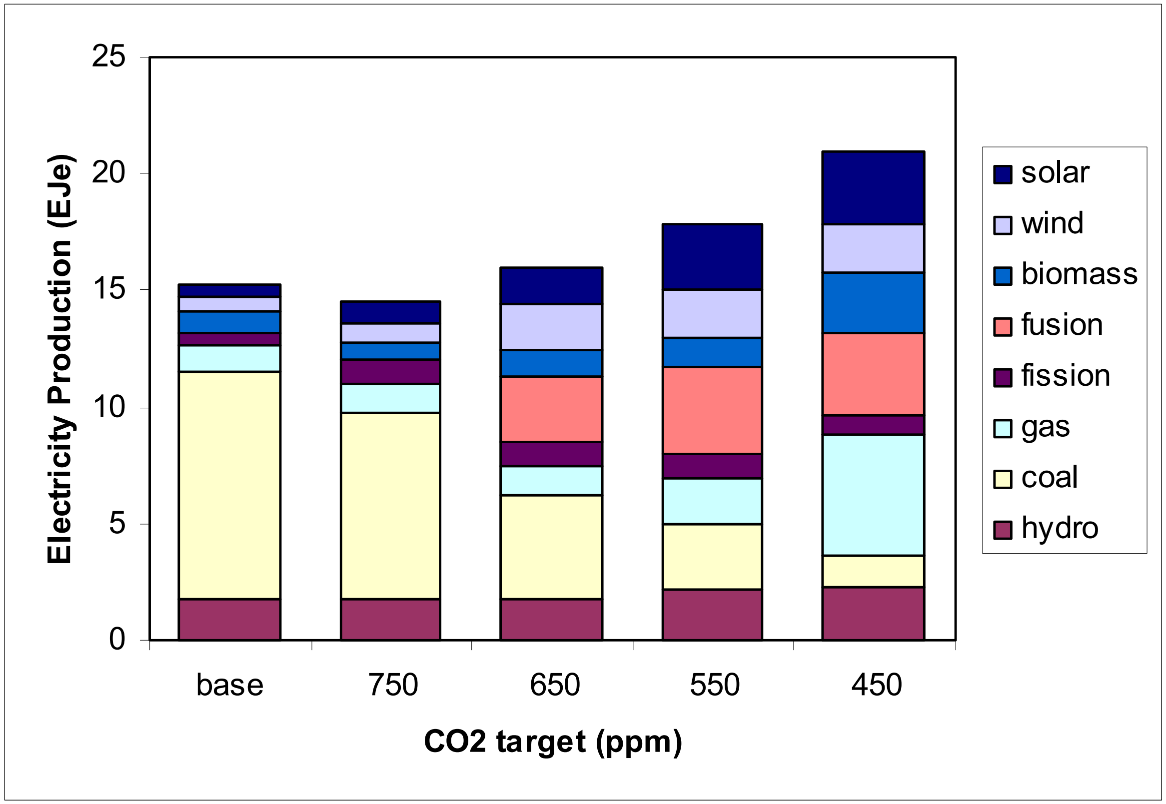
Externalities:

quantify in monetary terms adverse effects on the system (in most cases the environment) not already accounted for in the financial plan



fusion belongs to the class of low environmental impact energy systems

potential role of fusion:
role in energy scenarios for 21st century



electric power production in Europe in 2100:

scenarios

- minimizing total (discounted) expenditures for electric energy production in 21st century
- under different constraints on total CO2 production and on acceptance of fission

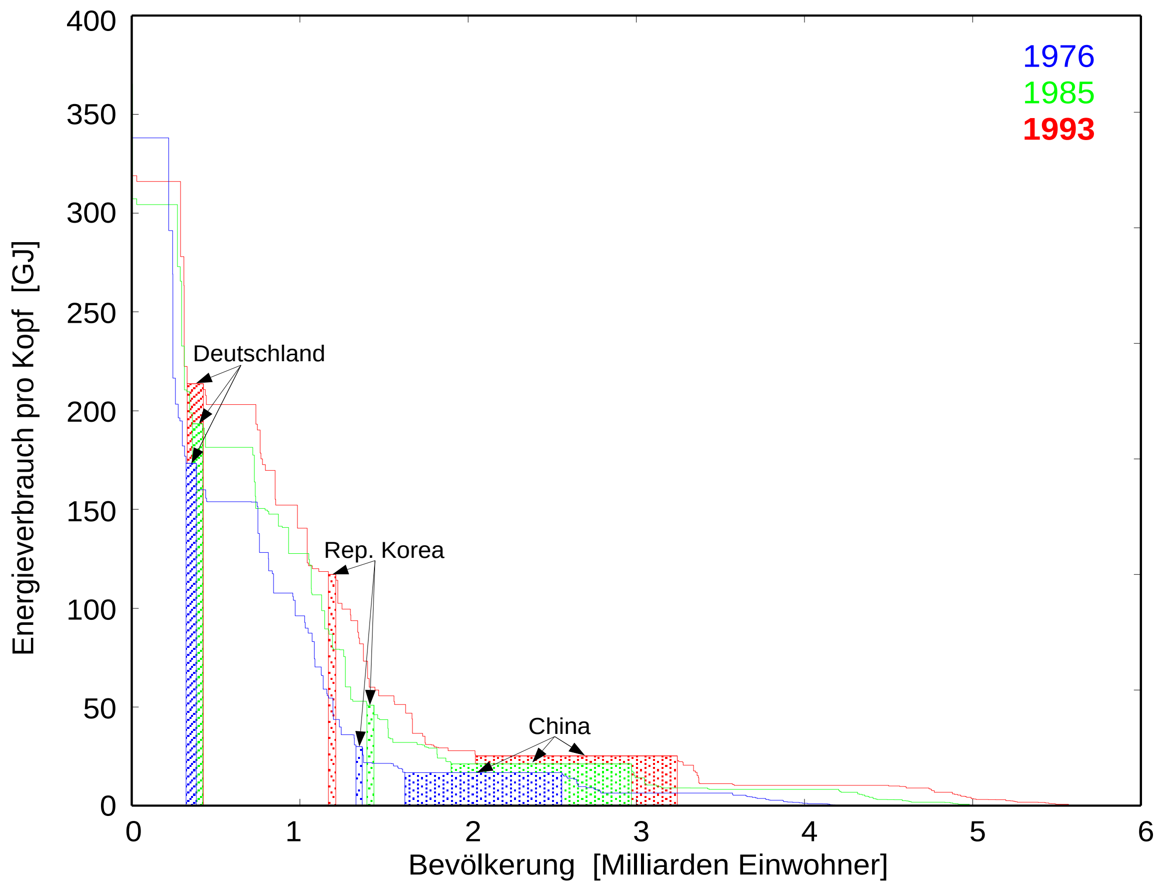
under CO2 emission constraints

- fusion could gain significant market share
- complimentary to classical renewables: fusion satisfies base-load demands

energy consumption growth: total and per capita

dramatic per-capita energy consumption growth at transition to highly developed country

at high per-capita consumption, a country has also technology capability for fusion

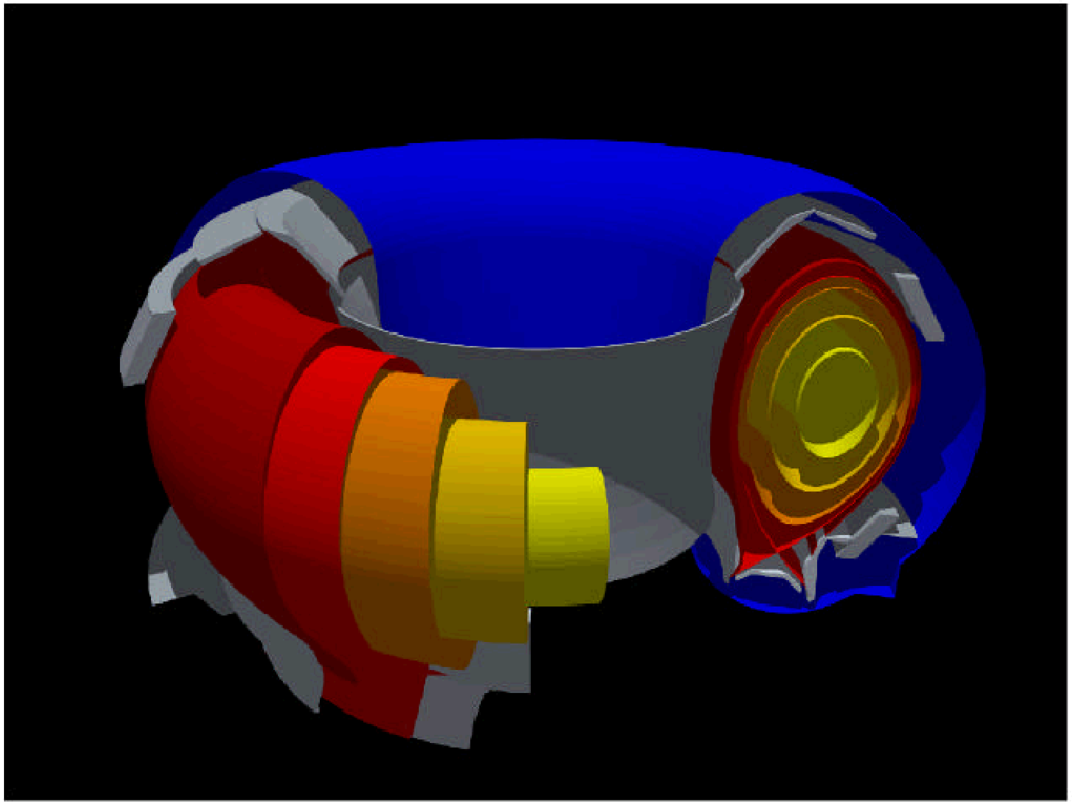


CarolusMagnus 1999

nested magnetic flux surfaces

large anisotropy of heat conductivity:

$\chi_{par}/\chi_{perp} > 10^{10}$



electromagnetics of a tokamak

Fully axisymmetric configuration

Toroidal field coils:

$\Rightarrow$ Toroidal magnetic field

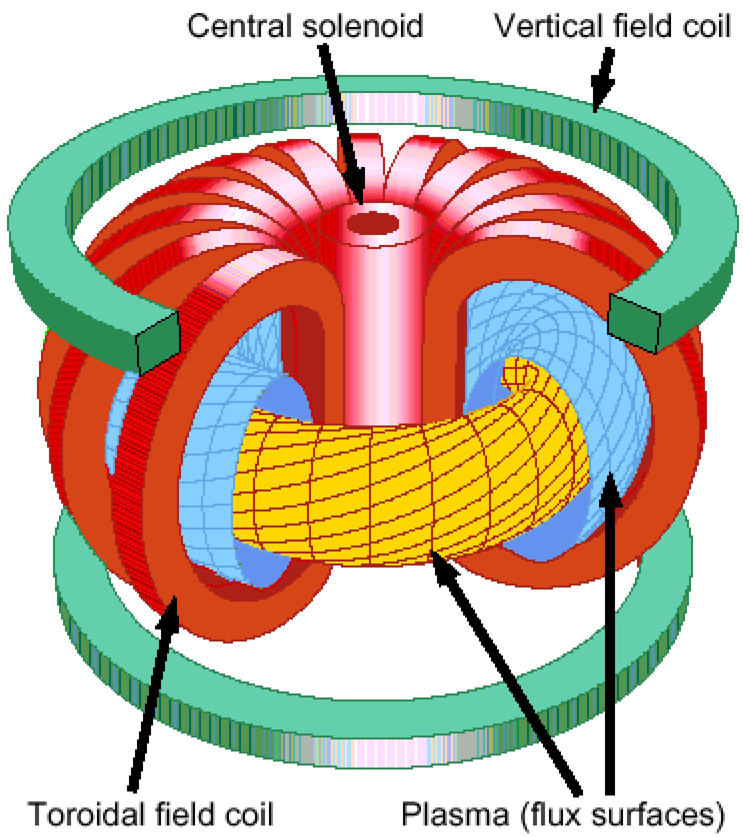
Central solenoid:

$\Rightarrow$ Inductively driven plasma current
$\Rightarrow$ Poloidal magnetic field

Vertical field coils:

"Equilibrium" - balance of hoop force

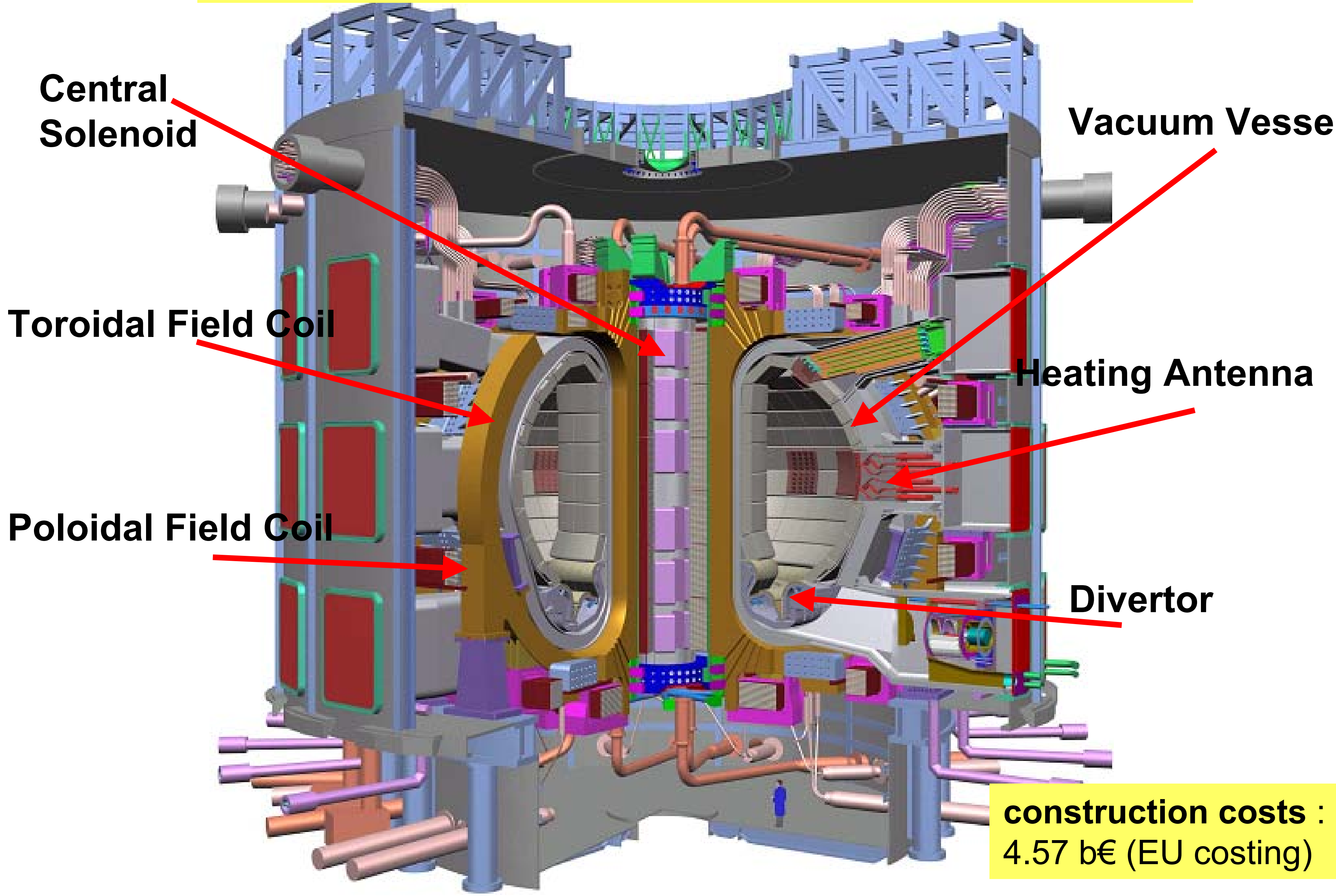
Shape of flux surfaces
(poloidal cross section)



ITER

Engineering Design Phase (1992 – 2001)
Japan + European Union + Russian Federation + (US until 1999)

negotiations among partners: above + (Canada) + China + USA(again)+ S. Korea



construction costs :
4.57 b€ (EU costing)

ITER´Mission

ITER Design Goals

- burning plasma physics
- integration of technology with physics
- demonstrate and test fusion power plant technologies

Physics:

•produce a plasma dominated by α-particle heating

•a significant fusion power amplification factor (Q ≥ 10) in long-pulse operation

•aim to achieve steady-state operation of a tokamak (Q = 5)

•possibility of exploring ‘controlled ignition’ (Q ≥ 30)

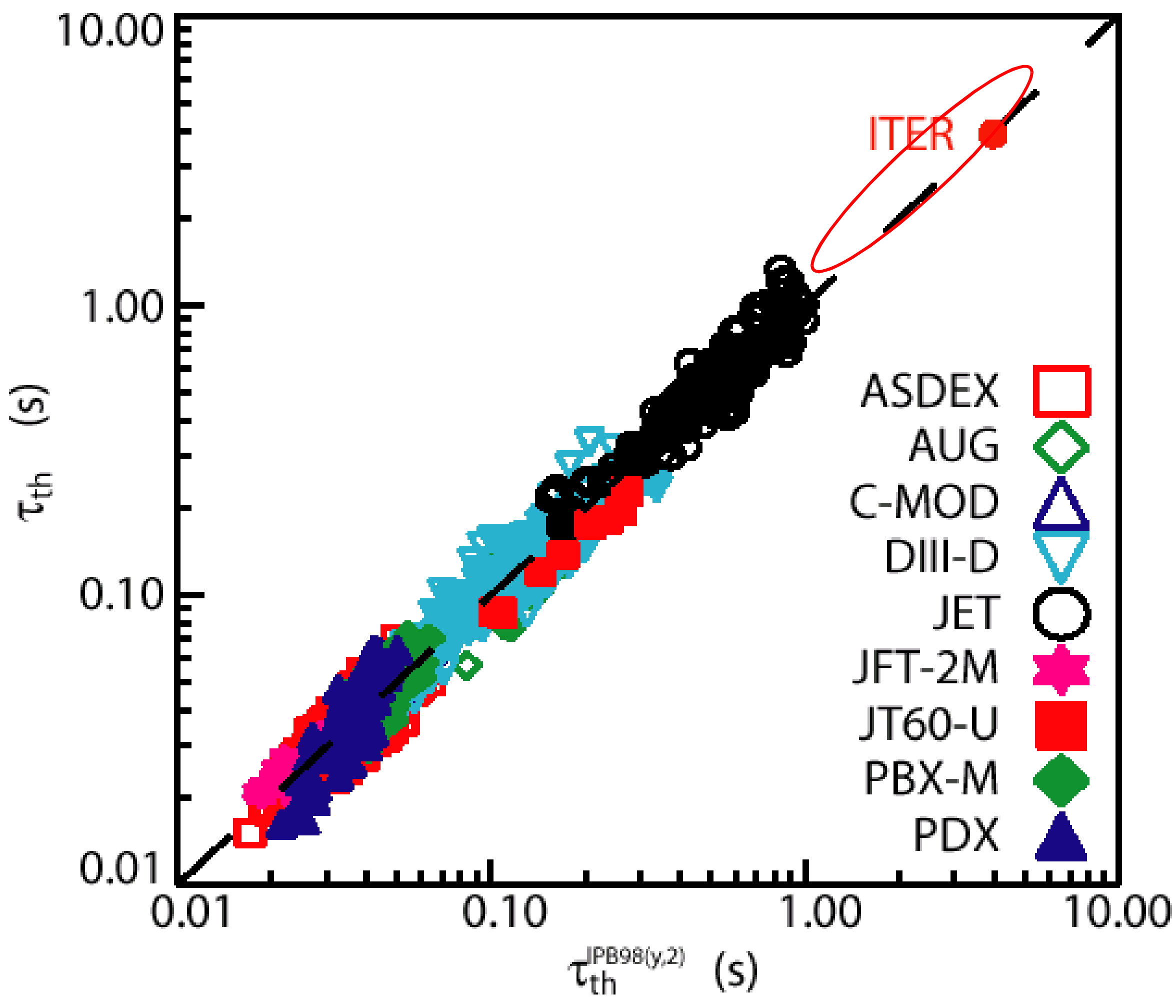
Technology:

•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´s Mission: physics of burning plasma - confinement in power plant grade (size) plasmas



Burning Plasma Physics
(1) explore plasma regime of a reactor

- Quasineutral plasma state characterized by 3 dimensionless parameters

$$\rho_i = \rho / R = 0.0032\sqrt{\mu_i T}/(RB_t)$$

$$\nu^* = Rq/\lambda_{mfp} = 10^{-22} R n_e q / T^2$$

$$\beta_t = 8\times10^{-22}\ n_e T / B_t^2$$

$$n_e = 1.3\times10^{16}\left(\frac{\mu}{R^2}\times\frac{\beta}{\rho^2}\right)$$

$$B_t = 1.1\times10^{-4}\left(\frac{q\mu^3}{R^5}\times\frac{\beta}{\nu\rho^6}\right)^{1/4}$$

$$T = 0.0011\left(\frac{q\mu}{R}\times\frac{\beta}{\nu\rho^2}\right)^{1/2}$$

- 4 dimensional ones: R, n, T, B
- dimensionless identity experiments
- a compact device with same plasma physics would require higher heating power, higher current than a reactor!

$$P_{heat} \propto R^{-3/4}$$
$$I_p \propto R^{-1/4}$$

- Fusion heating does not obey plasma physics constraints

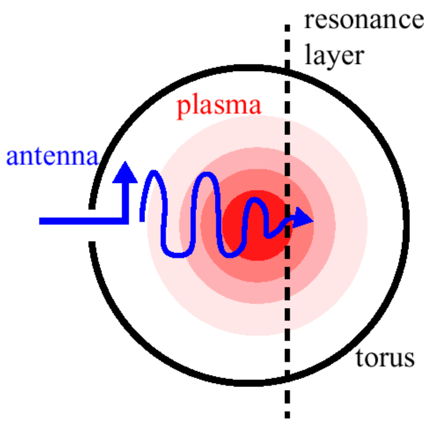
$$\frac{P_\alpha}{P_{heat,tot}} \propto nT\tau_E = f(\rho^*,\nu^*,\beta)\times R^{-5/4}$$

Device	R[m]	a[m]	Bt[T]	Ip[MA]	Pheat	nTτ (rel)
JET ext.	3	1.1	4	6	40	1
Ignitor	1.32	0.48	11.2 (<13)	7.4 (<11-12)	74 (35)	2.8

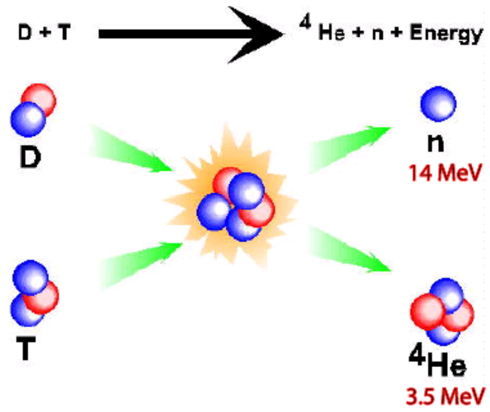
ITER´s Mission: physics of burning plasma - nuclear self-heating

tokamak operation so far:
external heating

e.g. wave heating



ITER: $nT\tau$ sufficient for dominant self-heating



$$Q = \frac{\text{fusion produced power}}{\text{externally applied heating power to plasma}} \rightarrow 10$$

dynamics of burn:
determined by

$$\gamma_b = \frac{1}{\tau_E}\left(\frac{d\log\langle\sigma v\rangle}{d\log T} + \left(1+\frac{5}{Q}\right)\left(\frac{d\log\tau_E}{d\log T}-1\right)\right)$$

(2) physics of fusion self-heating
global dynamics of ignition

- Global dynamics of ignition depends on plasma physics (ρ∗,ν∗, β) and T
- burn stability depends on confinement "law" and T;

$$\gamma_b = \frac{1}{\tau_E}\left(\frac{d\log\langle\sigma v\rangle}{d\log T} + \left(1+\frac{5}{Q}\right)\left(\frac{d\log\tau_E}{d\log T} - 1\right)\right)$$

  - for T-independent additional heating (not true, e.g. for Ohmic heating, which stabilizes due to opposite T-dependence)

- for physics of late 70ies (Alcator-Intor scaling, or even more CMG) and low temperature ignition a major issue.

$$\left(\frac{d\log\tau_E}{d\log T}\right)_{Alcator-Intor} = 0 \qquad \left(\frac{d\log\tau_E}{d\log T}\right)_{CMG} = 1 \qquad \left(\frac{d\log\langle\sigma\,\mathrm{v}\rangle}{d\log T}\right) > 2$$

- for scaling laws accounting for power degradation, and the higher operating temperatures forced by Greenwald limit - no issue

$$\left(\frac{d\log\tau_E}{d\log T}\right)_{H98(y)} = -1.7 \qquad \left(\frac{d\log\langle\sigma\,\mathrm{v}\rangle}{d\log T}\right) \le 2$$

(2) physics of fusion self-heating
α – particle physics

- Sufficient Q needed to dominate heating (Q=10, concur with Ignitor)

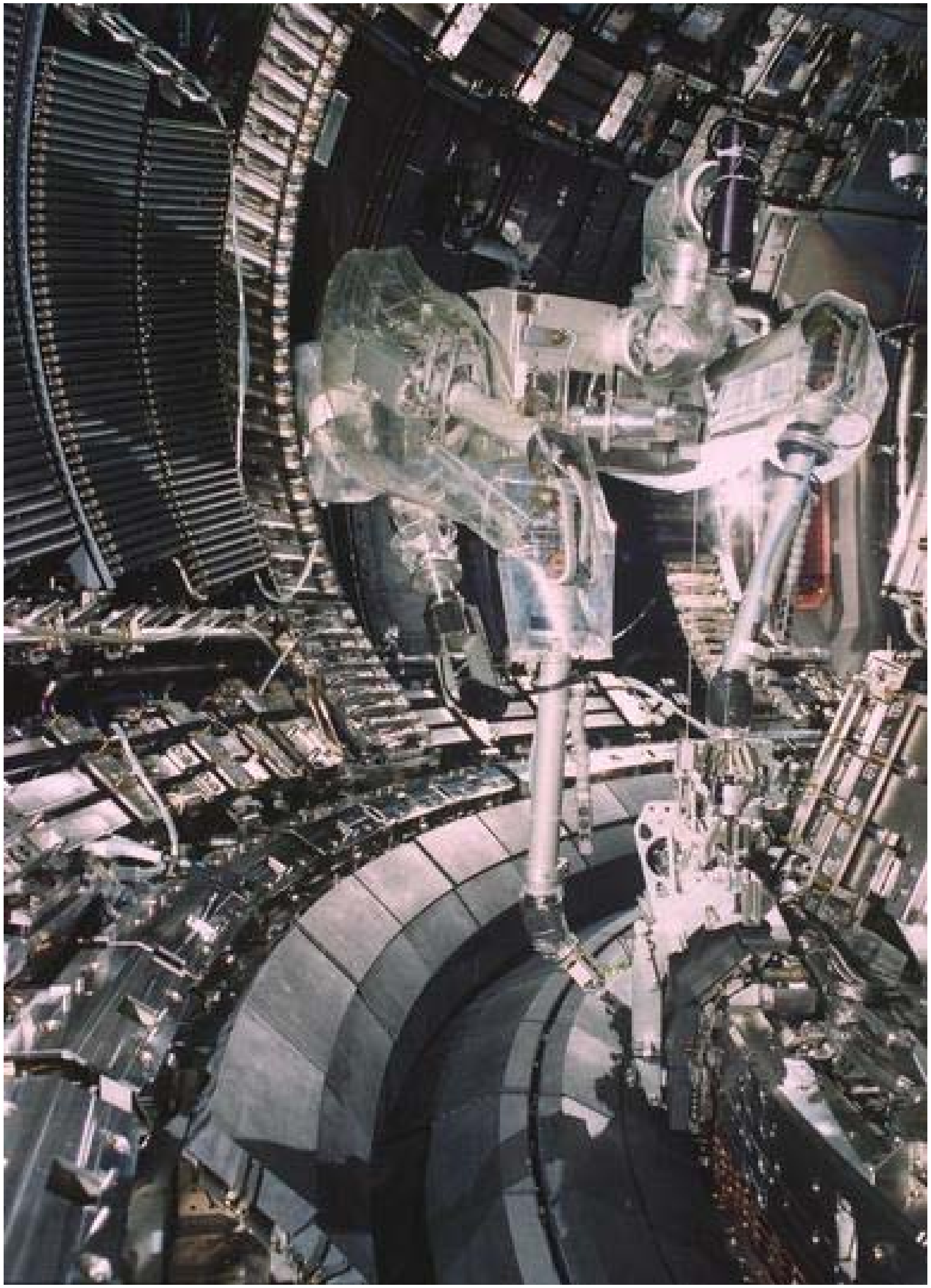
□ α-particle physics (via MHD-instabilities) depends (for given Q) on T,β

$$\frac{\beta_{fast}}{\beta} = \frac{P_{fus}\tau_{sd}}{P_{fus}\tau_E(1+Q/5)} \propto \text{(for fixed Q)}\ \frac{T^{3/2}}{n\tau_E} = \frac{T^{5/2}}{nT\tau_E} \propto T^{5/2}\left(\frac{T^2}{\langle\sigma v\rangle}\right)$$

- i.e. ignition temperature regime is essential for relevance of studies

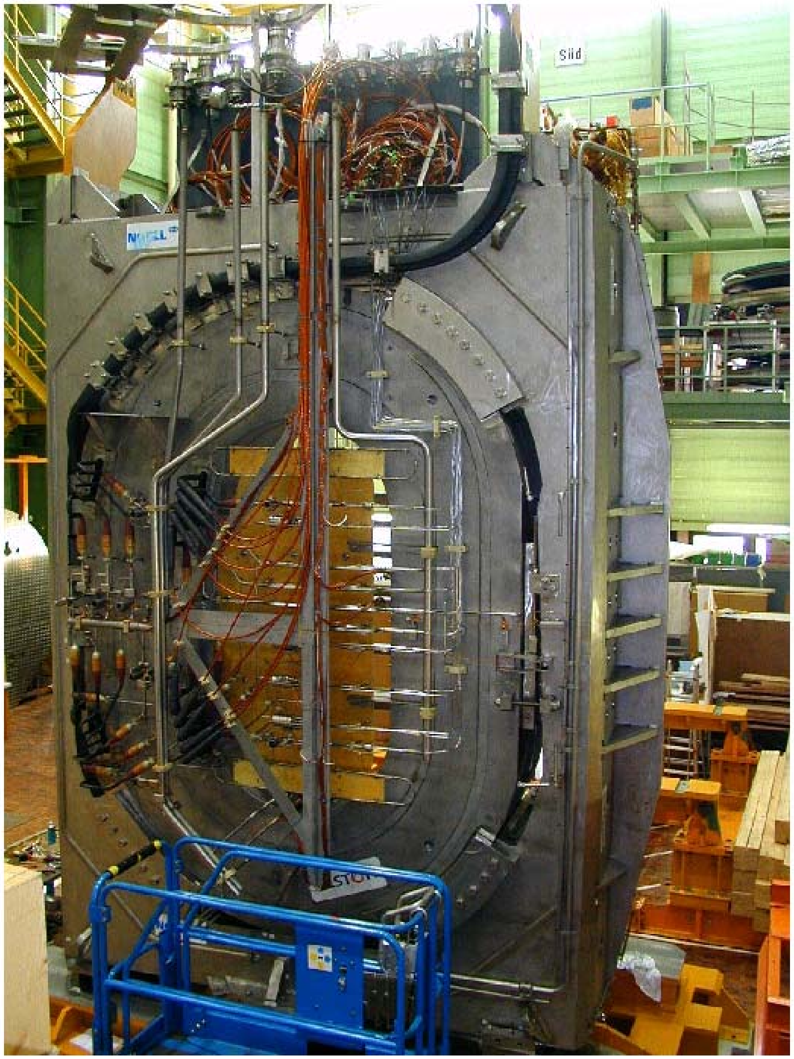
IPP

Preparatory R&D:
(some) key reactor technologies already on present devices



e.g.on JET: fully remote substitution of divertor structure under activated conditions (after DTE1)

Preparatory R&D: superconducting magnets (in burning plasma environment) - L1/L2



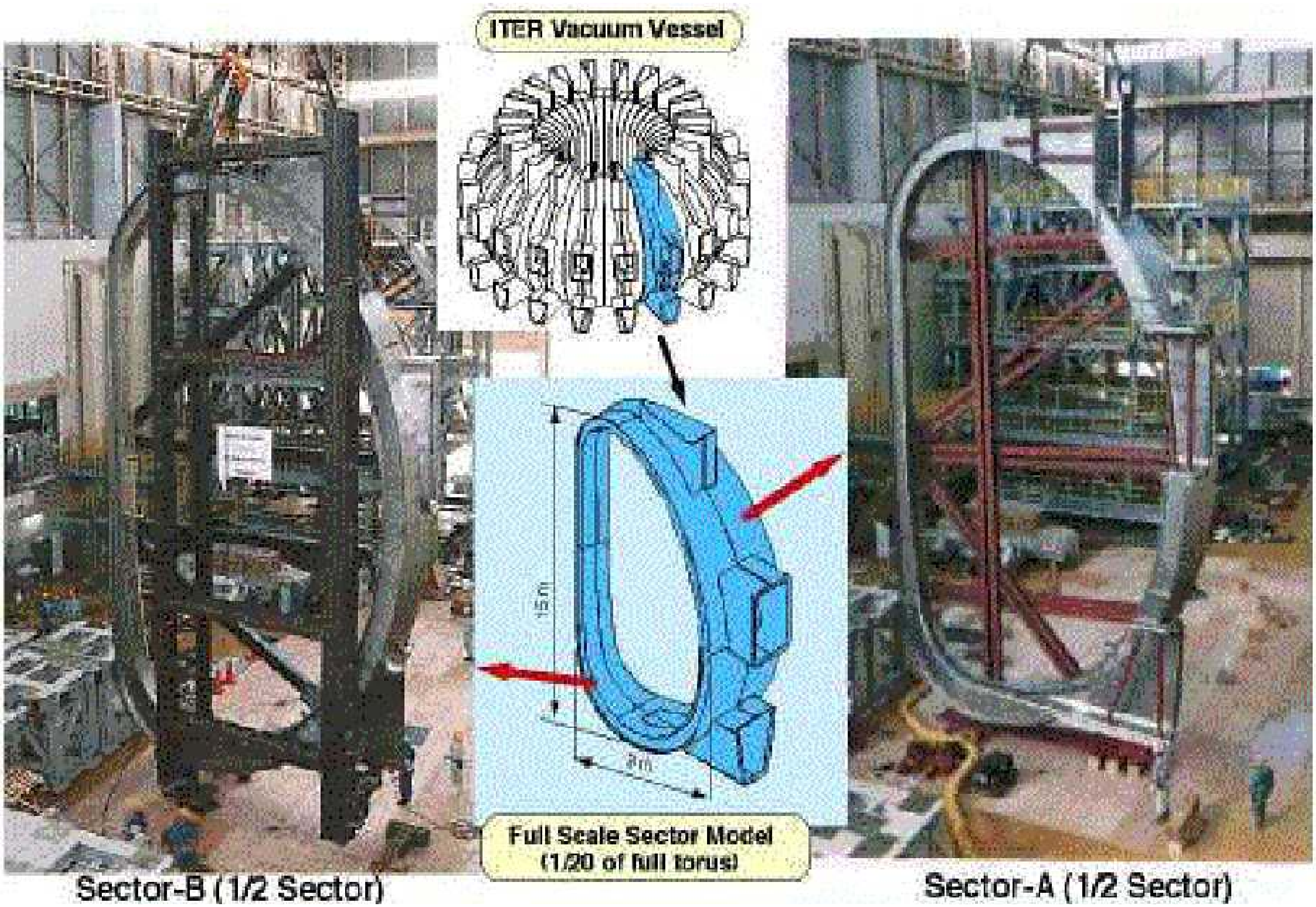
specific fusion technology had to be developed:

- high field, high stress (Ni_3Sn)
- rapidly time - varying magnetic fields

R&D for ITER (with strong involvement of industry and all 4 partners):

- test coils fabricated with record parameters (e.g. raised record for stored energy for Ni_3Sn by factor of 21, pulsed operation)
- developed industrial fabrication techniques

Preparatory R&D: Vacuum Vessel (L-3)



• View of full-scale sector model of ITER vacuum vessel completed in September 1997 with dimensional accuracy of ± 3 mm

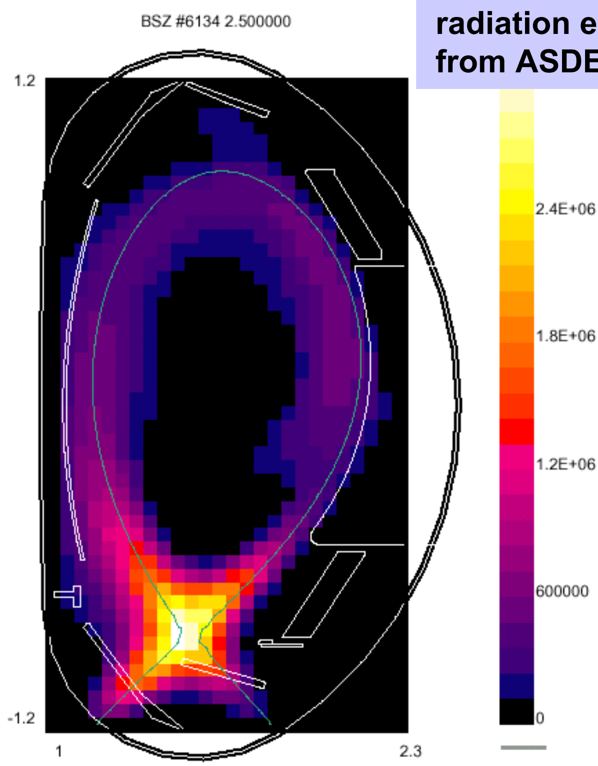
Preparatory R&D: Physics and technology cannot be separated:

e.g.: plasma-wall interaction

at plasma-wall contact large heat fluxes

unmitigated -> 60 MW/m^2
(comparable to sun surface)

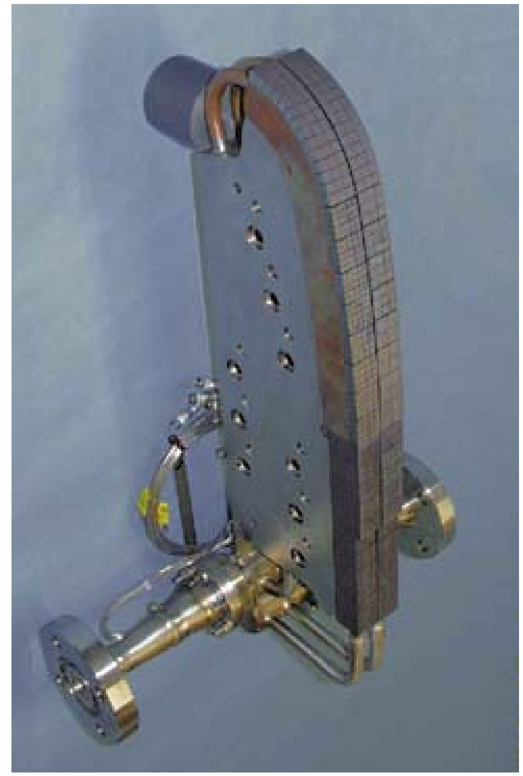
through plasma control (divertor)
-> 5-10 MW/m^2



radiation emission from ASDEX-Up

conversion of power flow into radiation:

prototype sustained 2000 cycles of 20 MW/m^2



have to be solved in symbiosis of research institutions with industry

Preparatory R&D: ITER component prototype development

Resource Allocation Summary for the Seven Large R&D Projects

(Unit: kIUA)

Projects	EU	Japan	RF	US*	Total
L1 - Central Solenoid Model Coil	10	**61**	4	**22**	97
L2 - Toroidal Field Model Coil	**40**	0	0	1	41
L3 - Vacuum Vessel Sector	4	**19**	4	2	29
L4 - Blanket Module	**29**	14	**12**	9	64
L5 - Divertor Cassette	13	12	9	**21**	55
L6 - Blanket Module Remote Handling	3	**18**	0	0	21
L7 - Divertor Remote Handling	**26**	3	0	0	29
Total	125	127	29	55	336

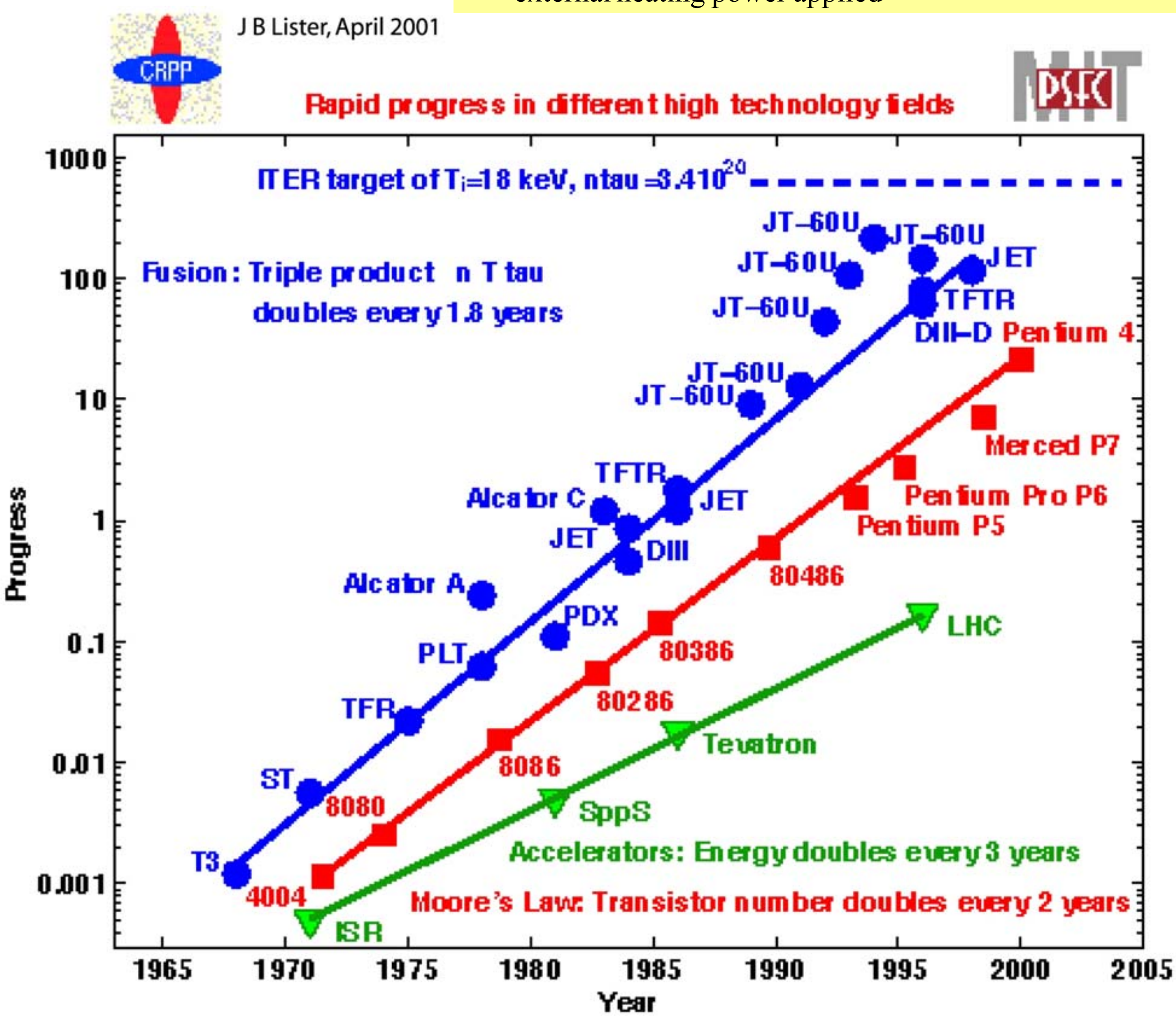
* US contributed until July 1999

Status: June 2000

The 1B$ ITER design effort and the 0.4 B$ spent on dedicated component development have produced a solid fundament and are a highly tangible asset of the ITER-project

Readiness for ITER: Fusion Research Performance can be measured in the „triple product“ *n T* τ

$$Q = \frac{\text{fusion power produced}}{\text{external heating power applied}} \sim n_{io} T_{io} \tau_E \quad (\text{for } Q << 5)$$



n... plasma density

T... plasma temperature

τ ... energy confinement time (a measure of the quality of the thermal insulation)

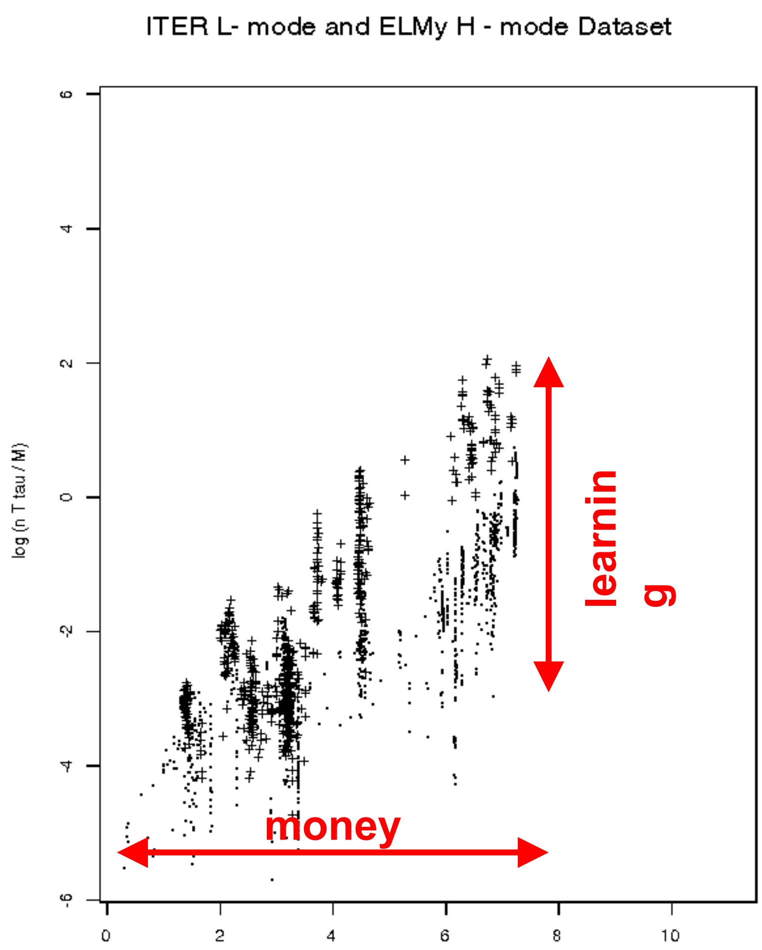
steady, rapid progress of tokamak performance

natural next step: burning plasma

tokamak research is mature for the step to a burning plasma - the progress in performance measure $n\ T\ \tau$

progress by:

- increased size of devices
- by improvements in design & operation

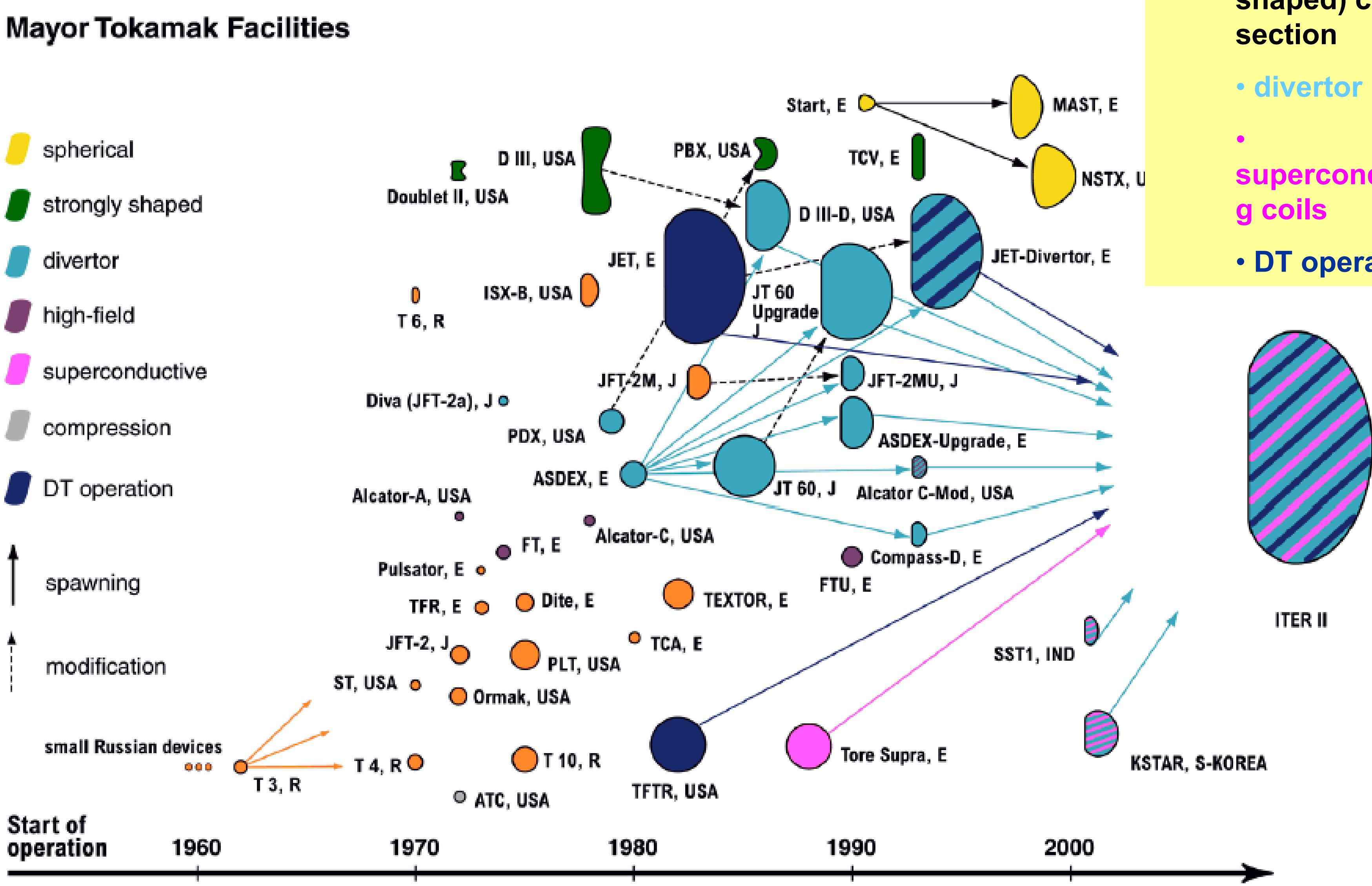


$$W_{magn} = \frac{B_t^2}{2\mu_o} \cdot V$$

Readiness for ITER: the (Darwinian) development of the tokamak concept

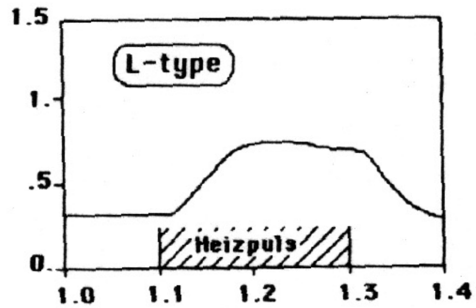
ITER incorporates all successfull developments:

- **elongated (D-shaped) cross-section**
- **divertor**
- **superconducting coils**
- **DT operation**

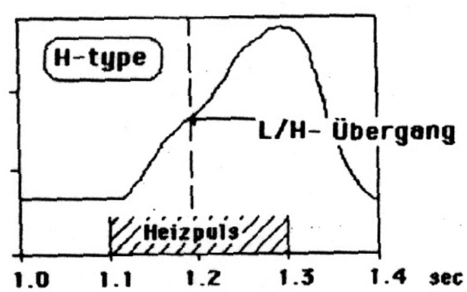


H-mode confinement or the unexpected side of plasma boundary physics - the tail wags the dog!

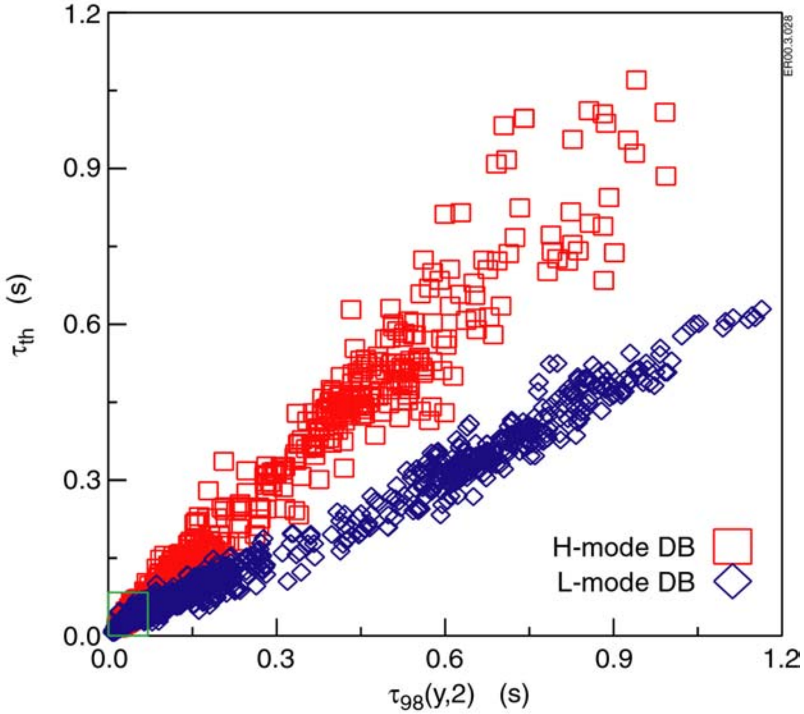
consequences on global confinement beyond those via impurity balance



16a



16b



historic questions:

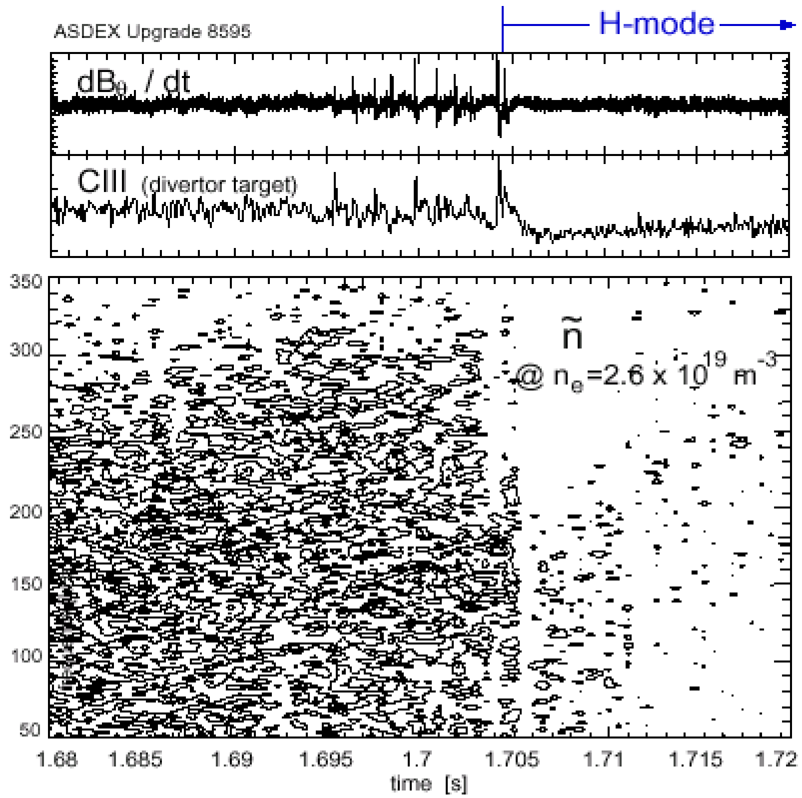
why only in divertors ?

why not internal barriers ?

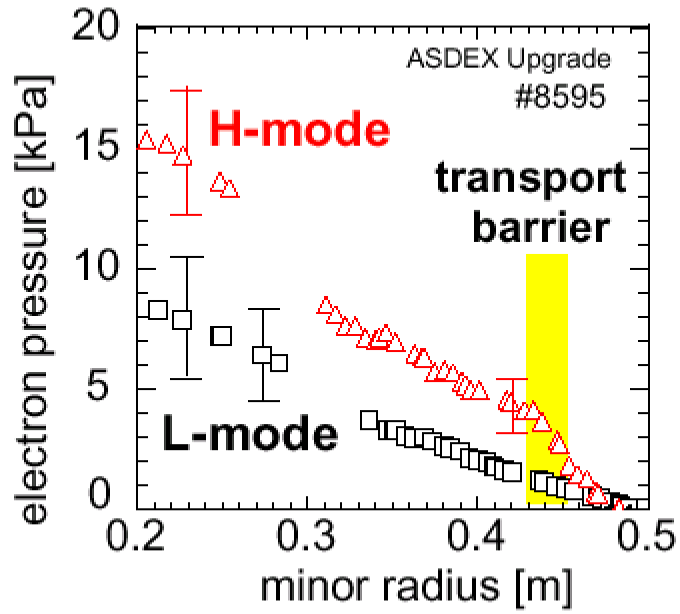
Transport barriers due to suppressed turbulence

1984 ASDEX:

Transition to H-mode = state with reduced turbulence at the plasma edge



Formation of an edge "transport barrier" = steep pressure gradient at the edge

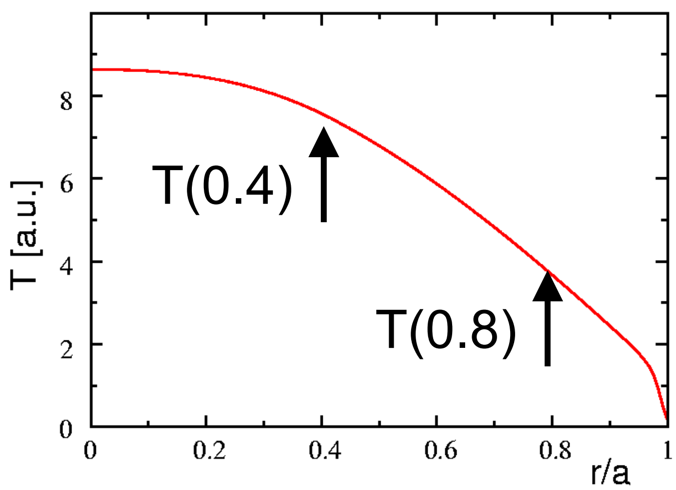


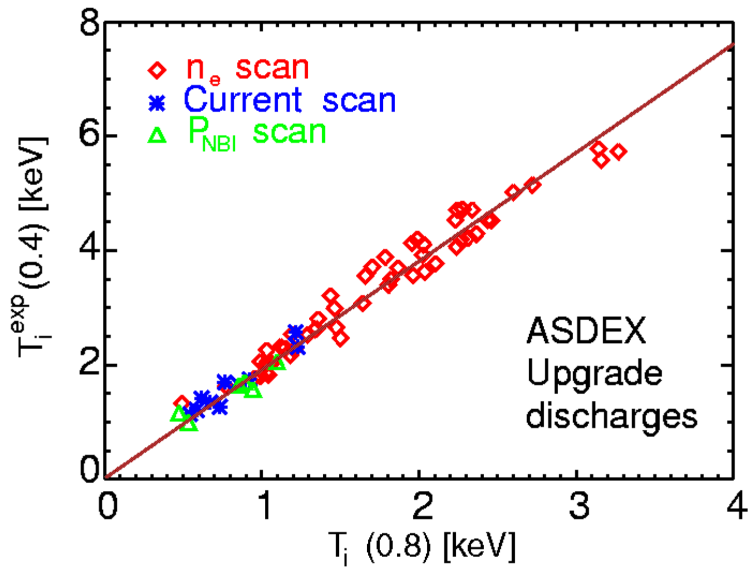
Reduction of transport coefficients to "neoclassical" level often found

Edge pressure limited by stability

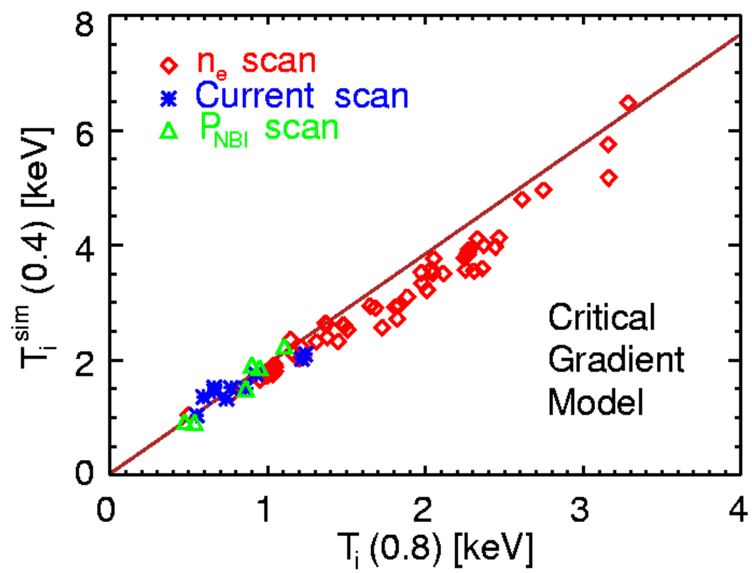
Theoretical understanding critical gradient modes causes “stiff“ temperature profiles

“Stiff” temperature profile found in experiment:
temperature at half radius proportional to edge temperature





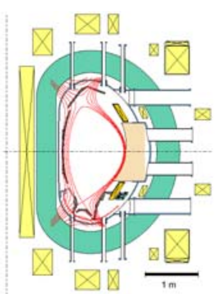
Simulation results reproduce measured temperatures



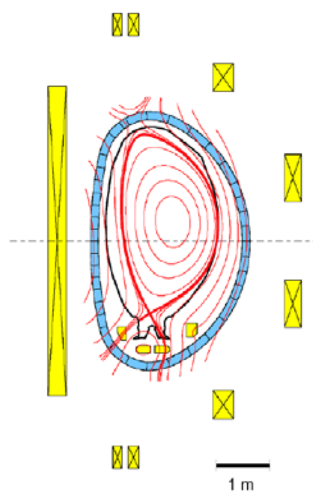
A. Peeters, G. Tardini

preparatory R&D in physics
„scaled versions of ITER “ available

(examples EU)

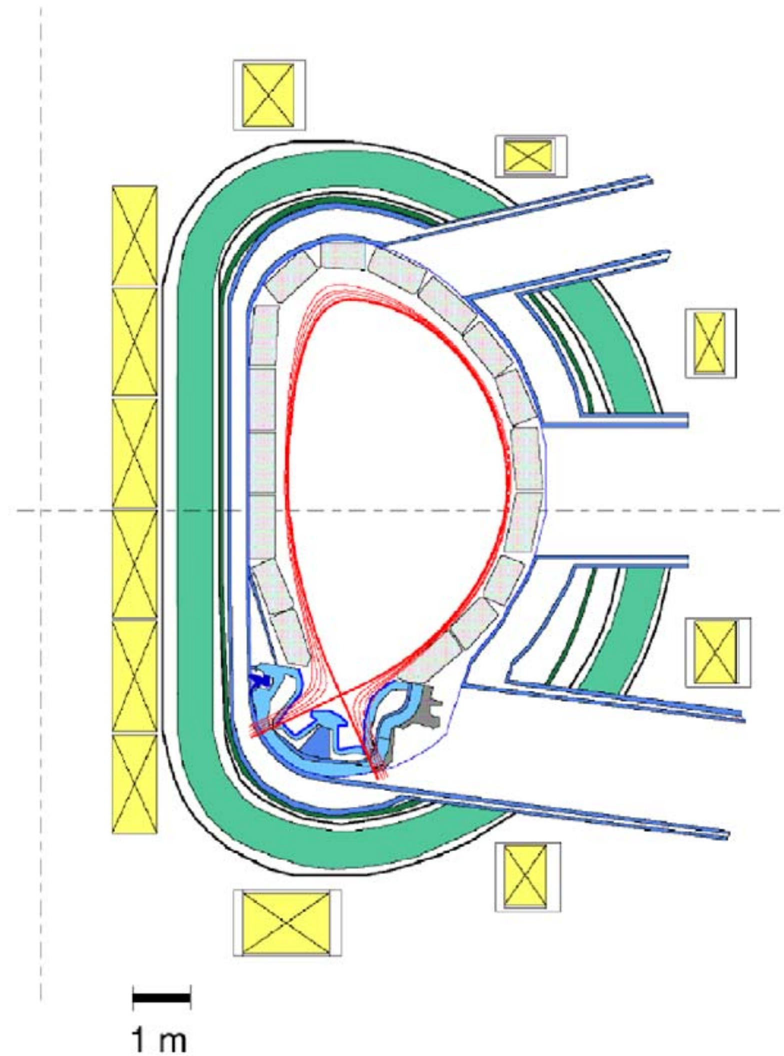


ASDEX-Upgrade
R = 1.6m



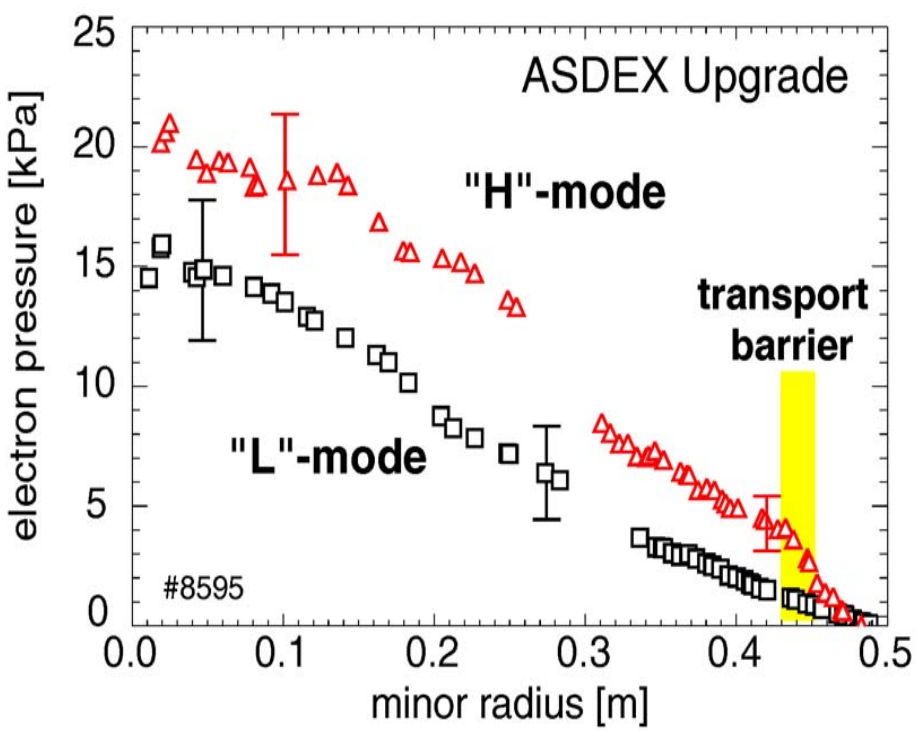
JET
R = 3m

ITER
R = 6 m

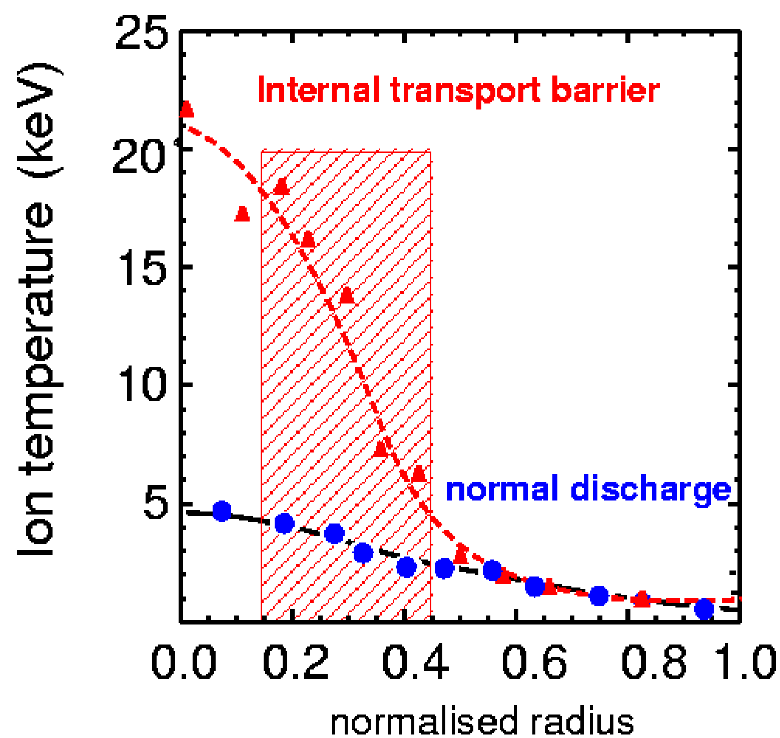


Transport barriers due to suppressed turbulence

Conventional Tokamak



„Advanced Tokamak“



For non-monotonic current profiles non-stiff profiles
Ignition Temperature on ASDEX Upgrade!

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 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

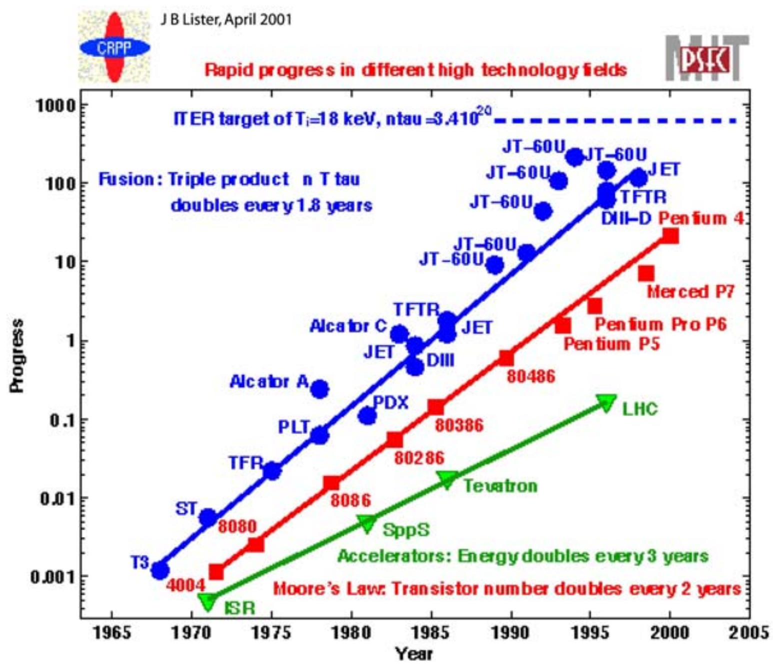
Standard inductive scenarios

1) verify & extend our scalings and theory models
(confinement, H-mode access, ELMs, NTMs..)

2) qualify α-particle heating as a heating method

3) high power/long pulse (on wall equilibration time) test of plasma wall interaction (incl. tritium inventory control)

maintain momentum:



Q= 10 reference scenario(s): milestone

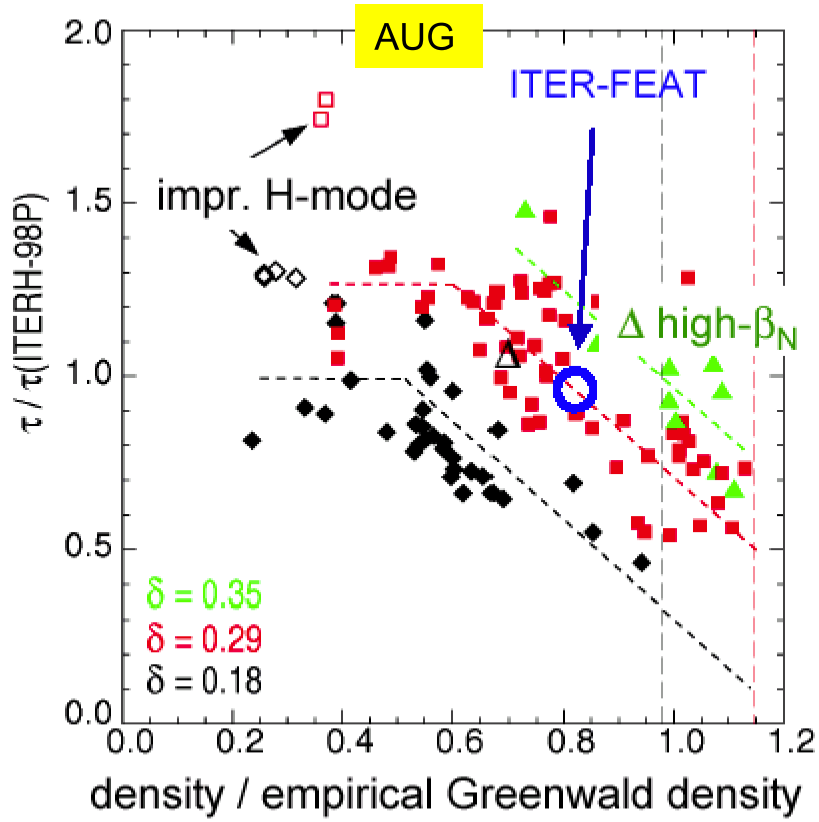
IPP

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

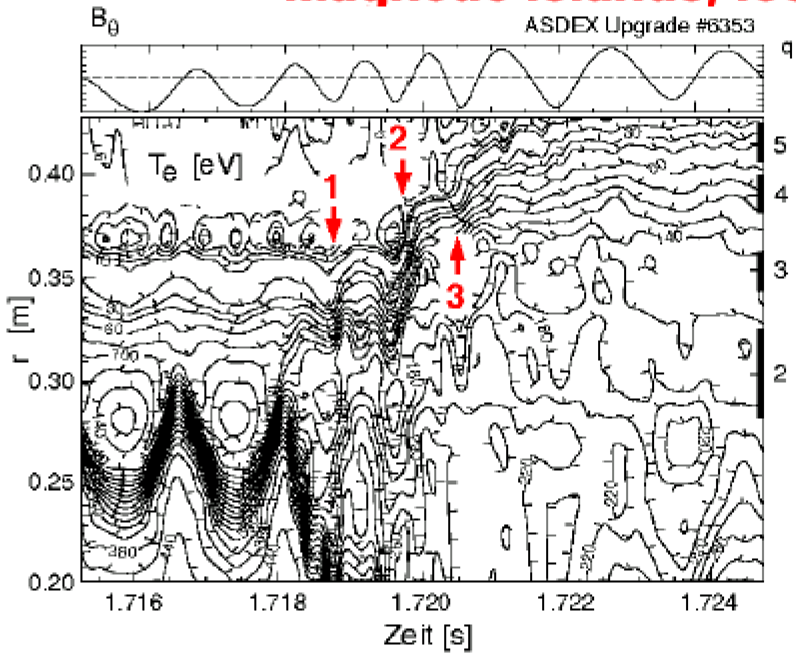
conservative requirements

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



Magnetic islands, loss of confinement

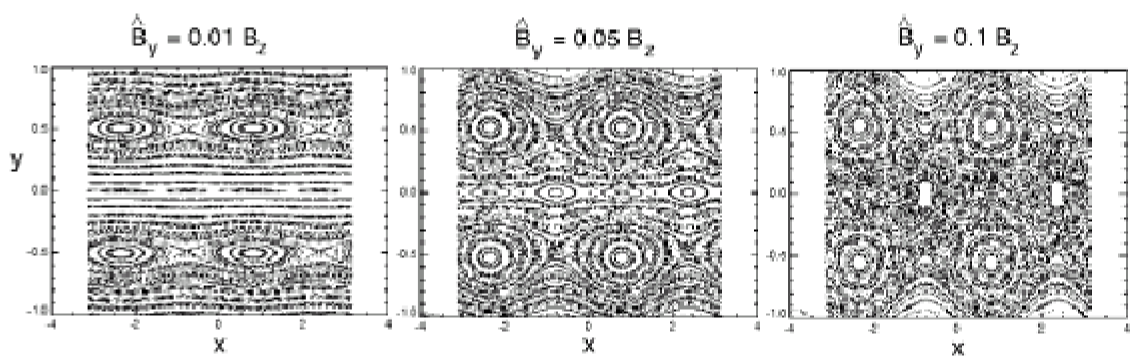


Diagnostic: Te constant on flux surface
Rotating islands give 2D "image"

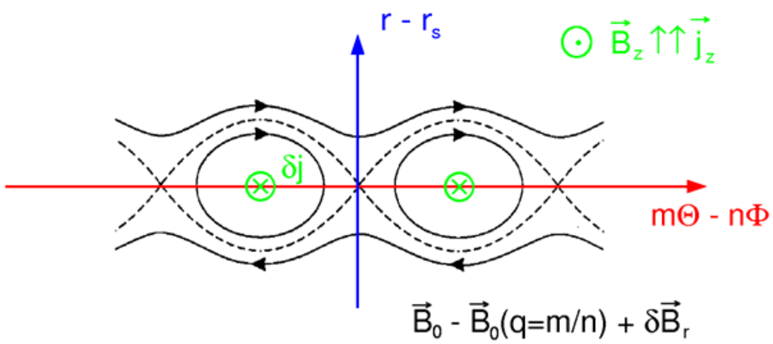
Temperature profile flattens between islands

Possible reason:
Large islands with different helicity
→ Ergodisation of field lines

Field line tracing model (slab):

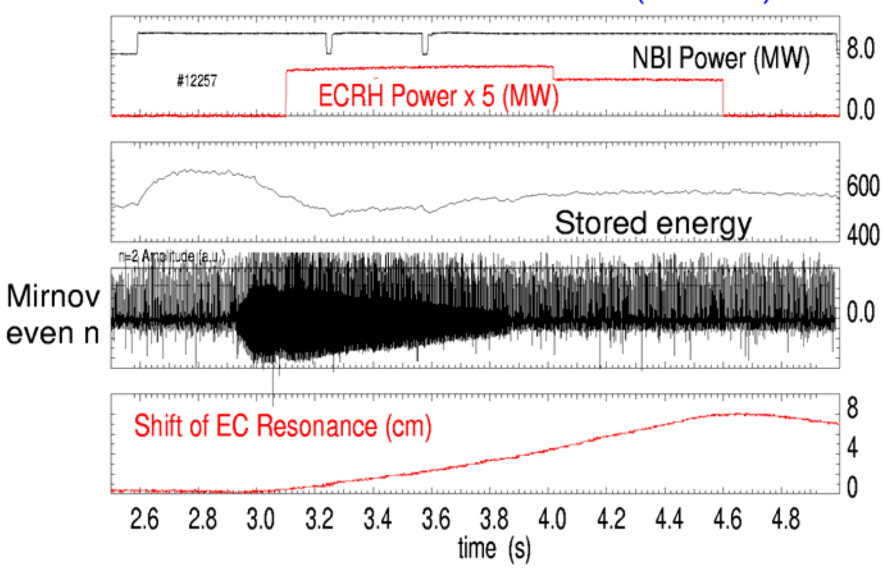


active stabilization of NTMs



Missing bootstrap current inside island can be replaced by localised external current drive.

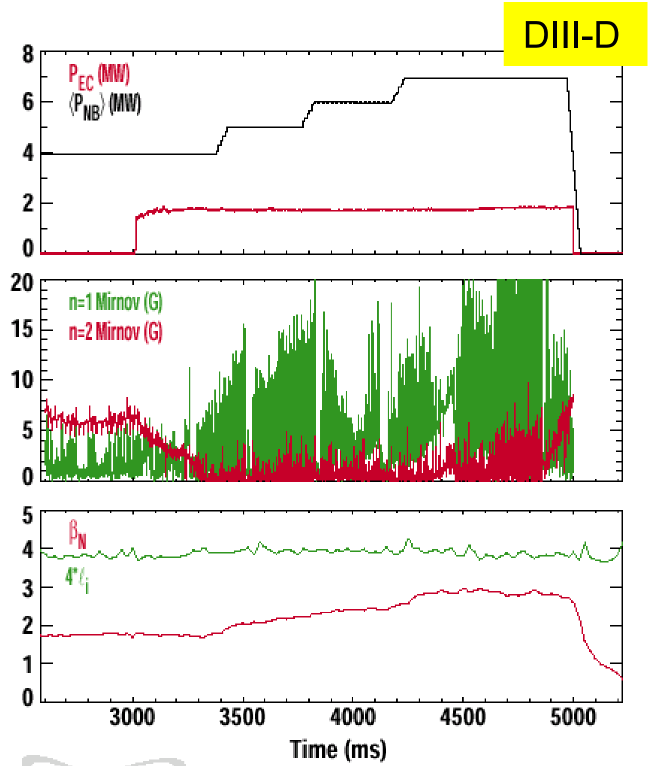
non-modulated co-ECCD (AUGD)



Complete stabilisation in quantitative agreement with theory!

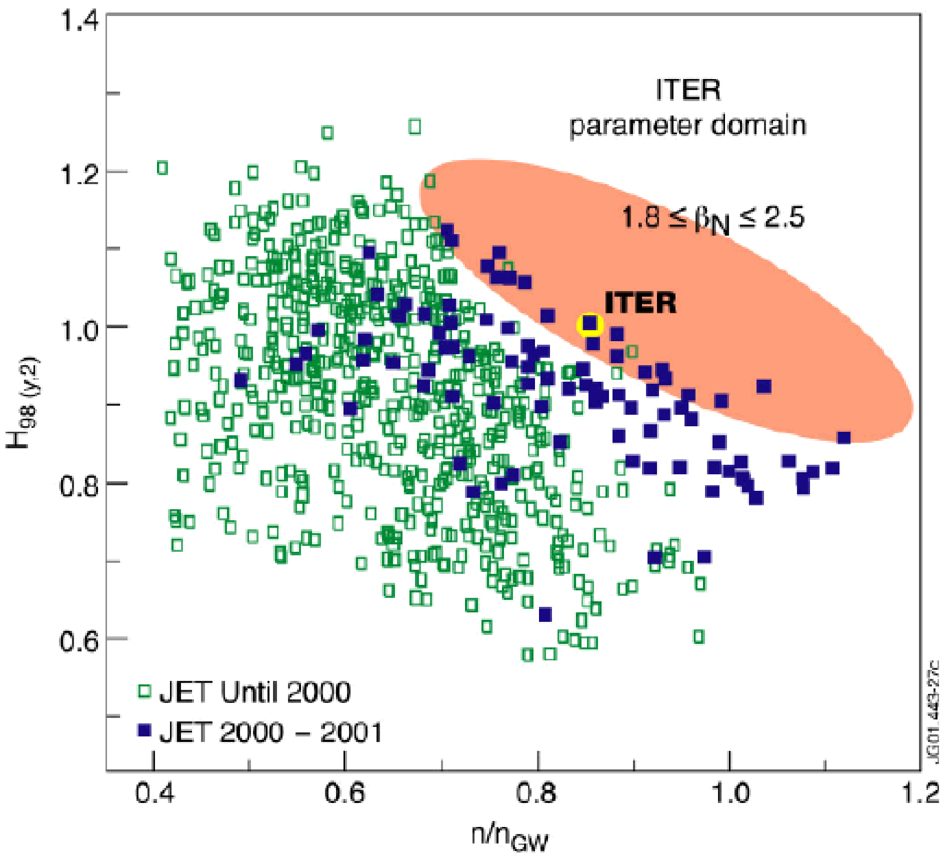
high confidence level in attainment of Q =10
results of targeted R&D

- NTMs:
  1) active ECRH-feedback

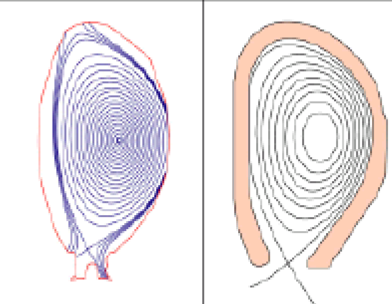


  2) self-limitation: FIR-modes (AUG/JET)
  3) control of sawteeth (JET)

Q =10: ITER-simulation discharges on JET



JET-operating space

SHAPING	
	
JET "ITER shape" Pulse No: 53299, 2.5MA/2.7T	**ITER**

	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**

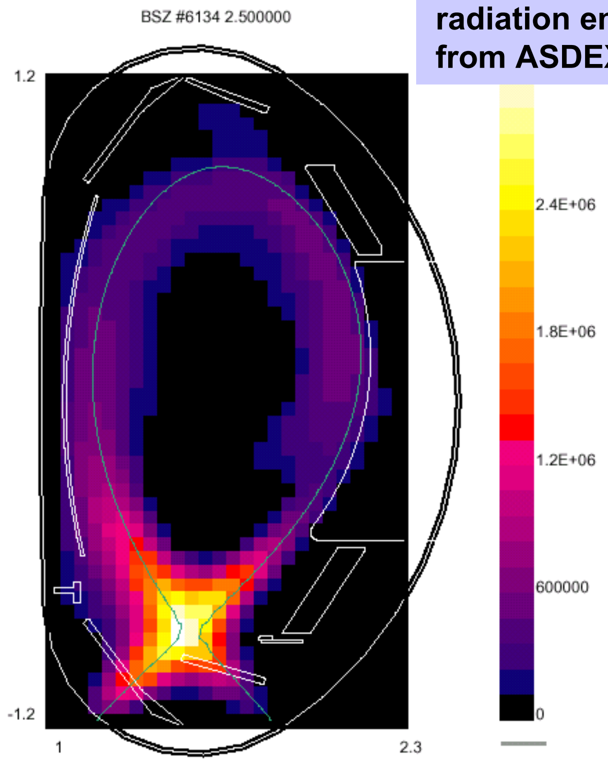
Preparatory R&D: Physics and technology cannot be separated:

e.g.: plasma-wall interaction

at plasma-wall contact large heat fluxes

unmitigated -> 60 MW/m^2
(comparable to sun surface)

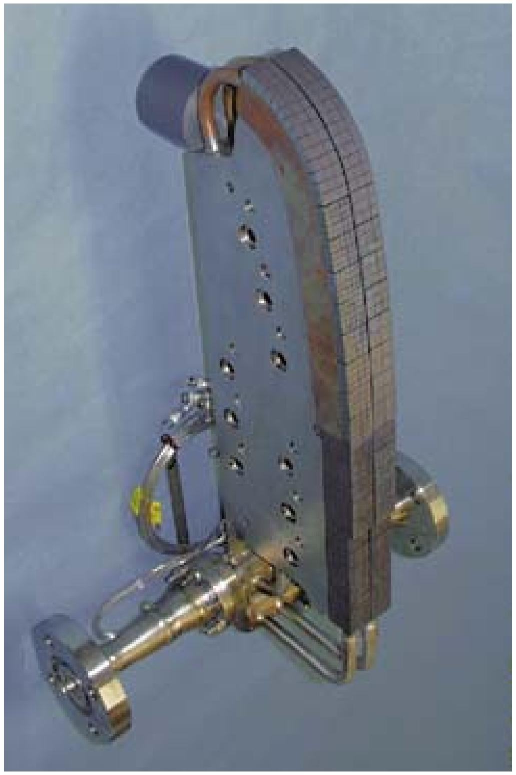
through plasma control (divertor)
-> 5-10 MW/m^2



radiation emission from ASDEX-Up

conversion of power flow into radiation:

prototype sustained 2000 cycles of 20 MW/m^2



have to be solved in symbiosis of research institutions with industry

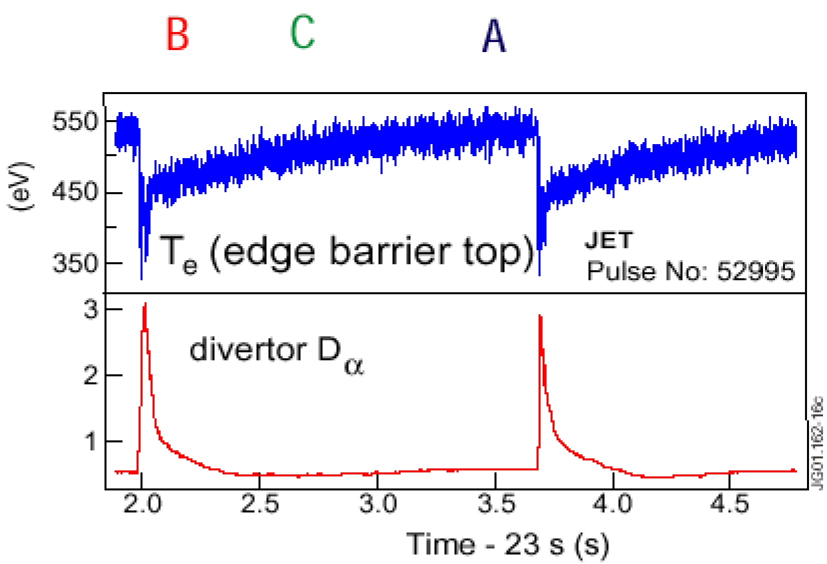
Edge Localised Modes (ELMs)

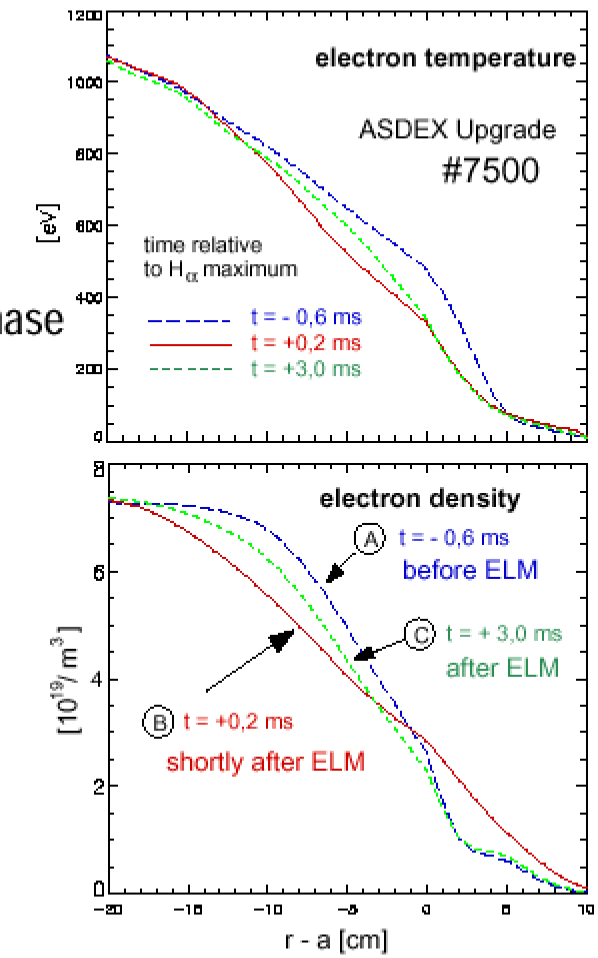
ELM oscillations:

A. Critical ∇p in H-mode barrier region reached
Short unstable phase (ELM event)

B. Energy and particle loss has lead to reduced gradients

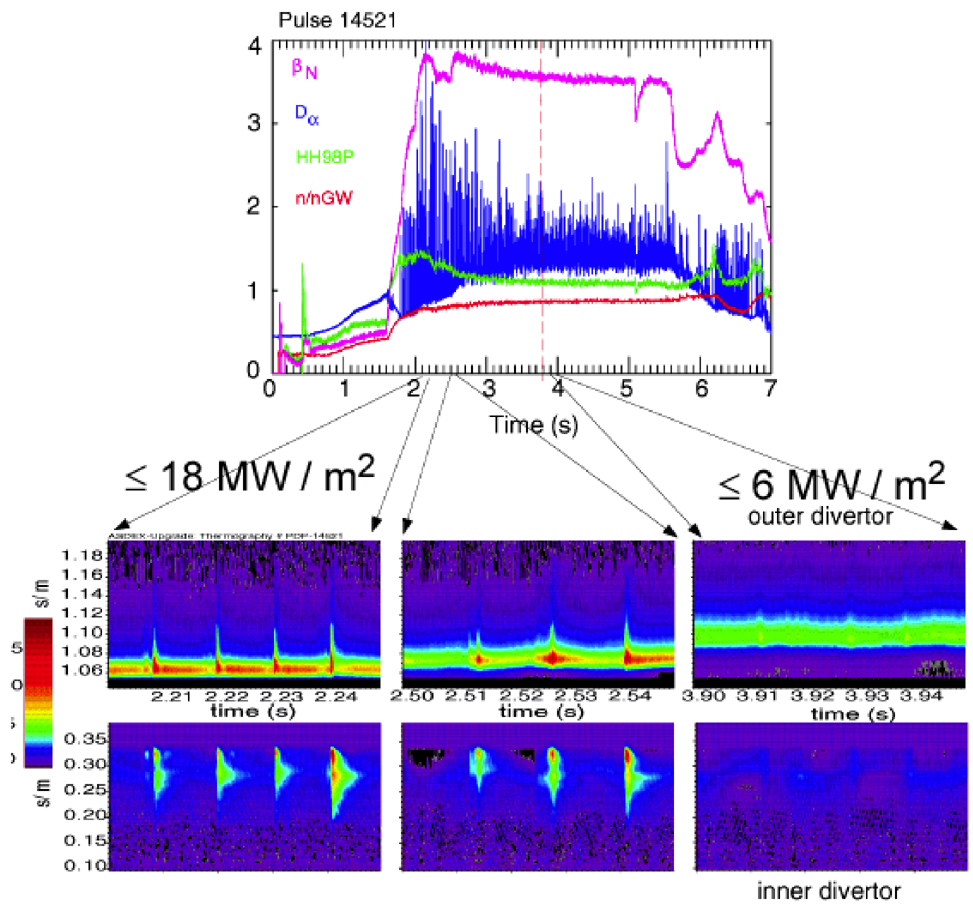
C. Gradients build up during reheant/refuelling phase





Q =10: divertor issues

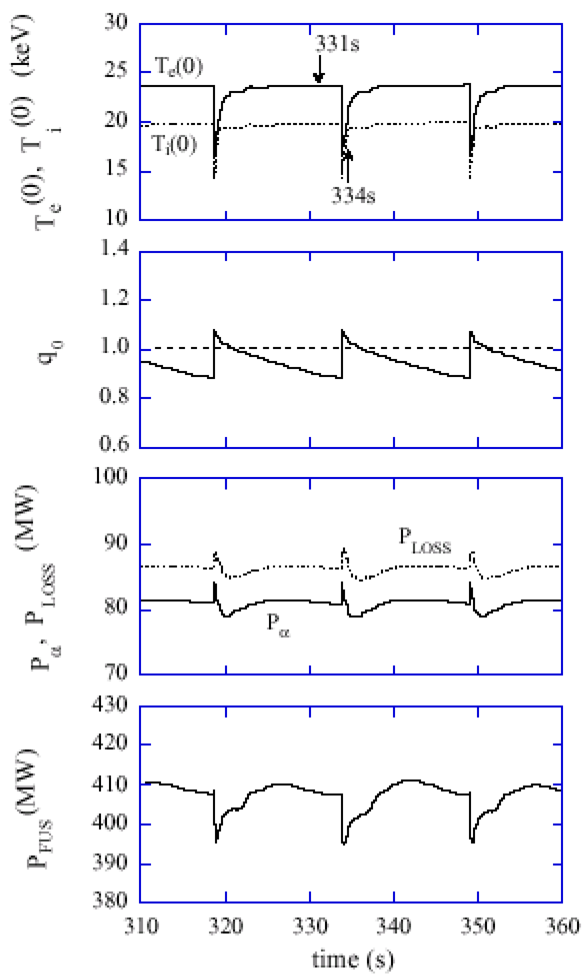
- **divertor & plasma wall interaction issues (ELM tolerance, tritium):**
  - determine pulses: how long & how often
  - has to be solved for any kind of fusion reactor
  - focussed effort starts bearing fruit
    - type 2 ELMs
    - control of C erosion & tritium co-deposition by surface temperature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



Q =10: α–particle effects

α-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 α–particles**
- fishbones: **(marginally) unstable for nominal parameters**



sawteeth:

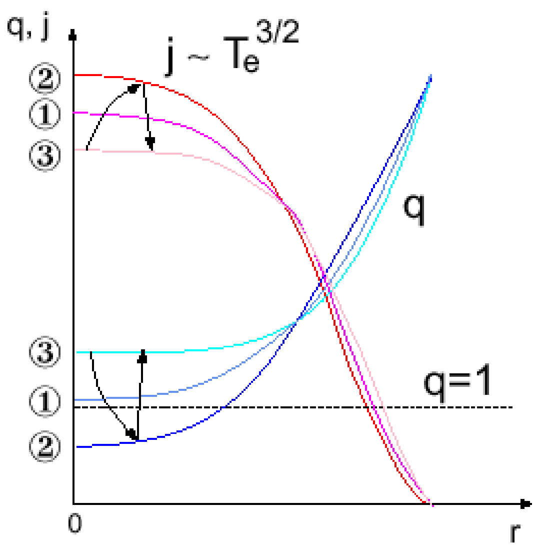
•period extended by α-particle stabilisation

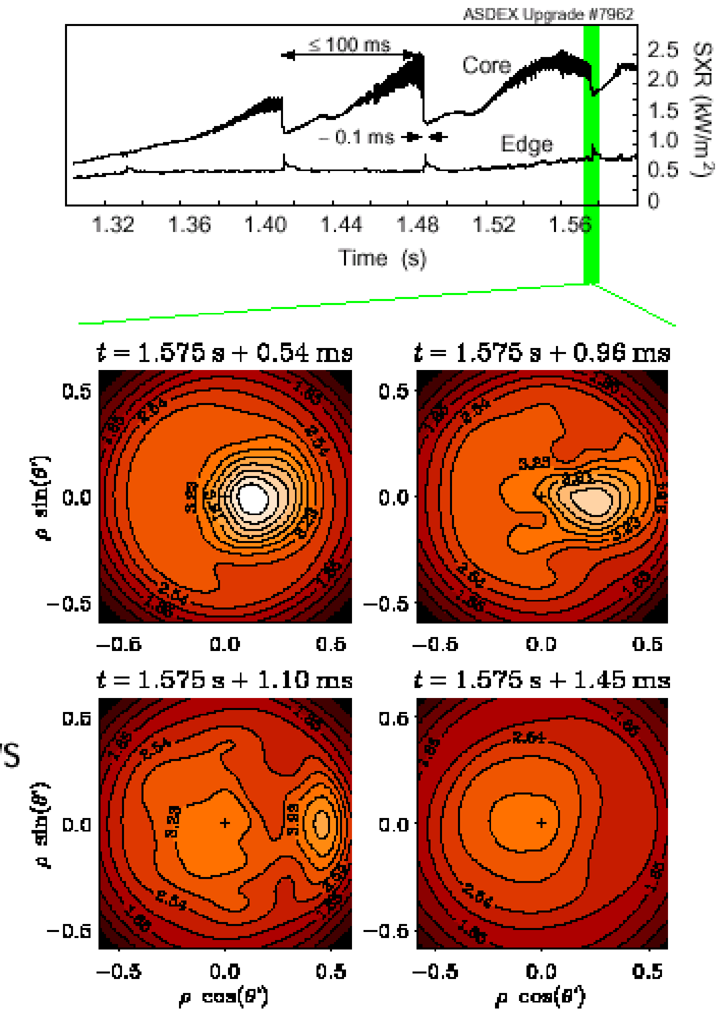
•30% central T-excursion

•small effect on heat flux

Sawtooth oscillations

Central profiles:





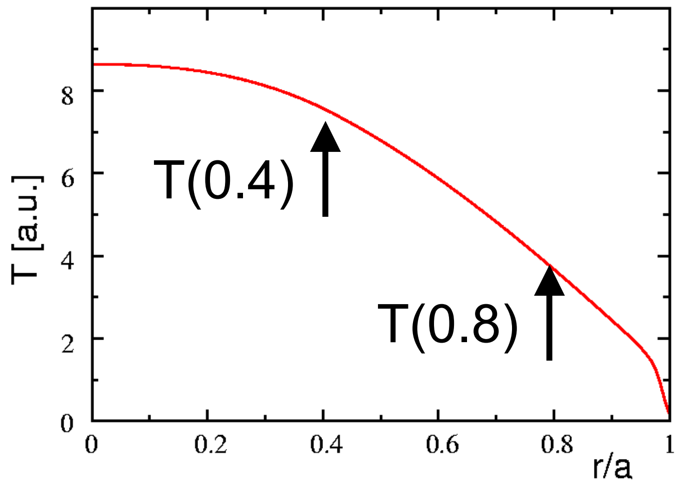
① T(0) and $j(0) \propto T^{3/2}$ rise

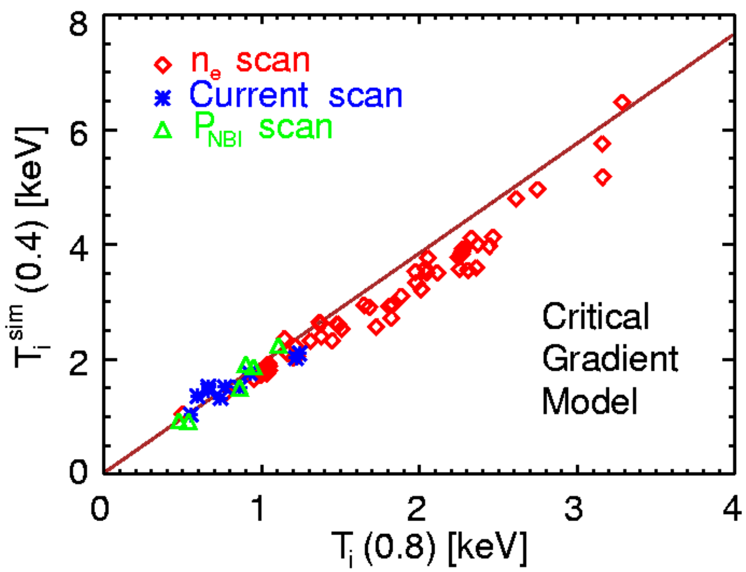
② q(0) falls below 1 → kink instability grows

③ Fast reconnection event:

T, n flattened inside q=1 surface
q(0) rises slightly above 1, kink stable

missing understanding: scaling of pedestal?

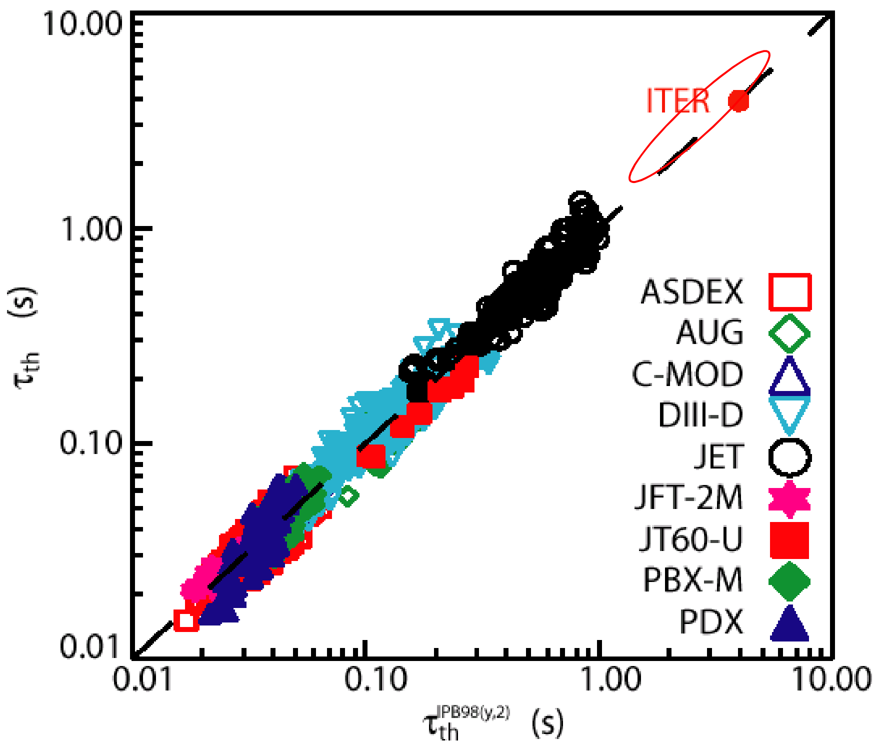




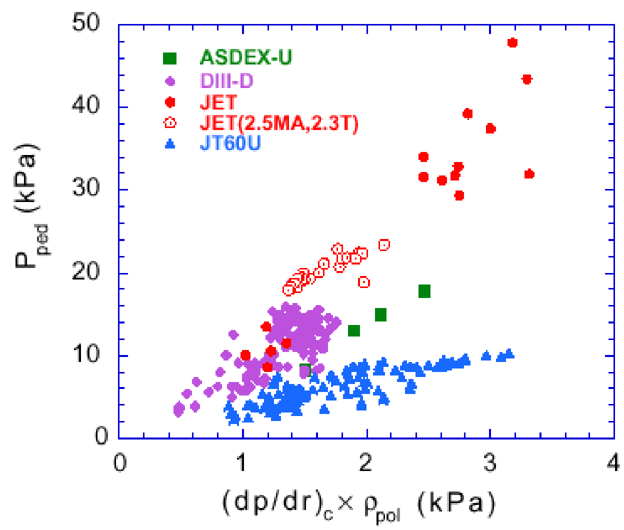
in simulations: pedestal parameters assumed input

A. Peeters, G. Tardini

Extend scaling and verify theory: confinement

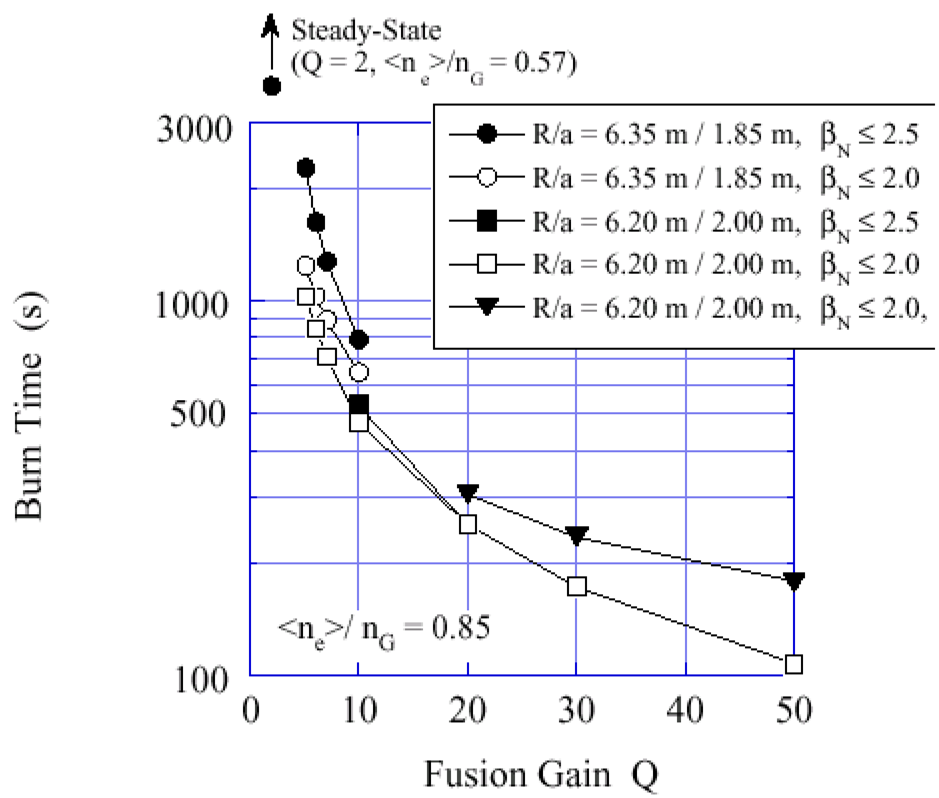


- pedestal scaling
  - pressure gradient limited
  - spatial scale? $R^{\alpha}\rho^{1-\alpha}$



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

hybrid scenario: conservative scenario for technology testing

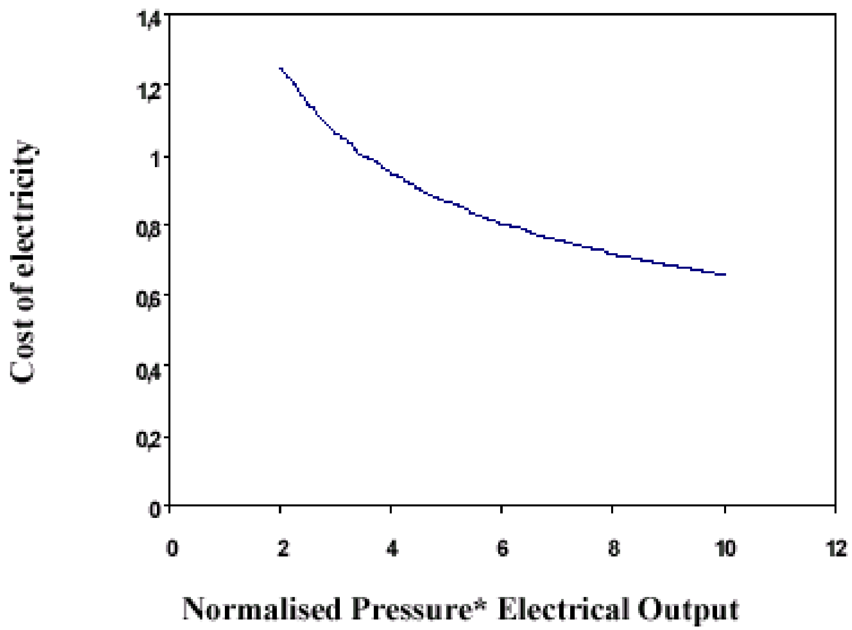


	Scenario 3
	Hybrid #1
R (m)/a (m)	6.2/2.0
κ_{95}/δ_{95}	1.7/0.33
V_P (m^3)	831
B_T (T)	5.3
I_P (MA)	13.8
q_{95}	3.3
$\langle n_e \rangle$ ($10^{19}m^{-3}$)	9.3
$\langle n_e \rangle / n_G$	0.85
$\langle T_i \rangle$ (keV)	8.4
$\langle T_e \rangle$ (keV)	9.6
β_N	1.9
P_{FUS} (MW)	400
P_{NB} (MW)	33
P_{RF} (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**
  - **α-physics compatibility**
  - **long pulse aspects**
    - **current profile**
    - **plasma surface interaction**
  - **heating power > current drive power**
    - **controllability**



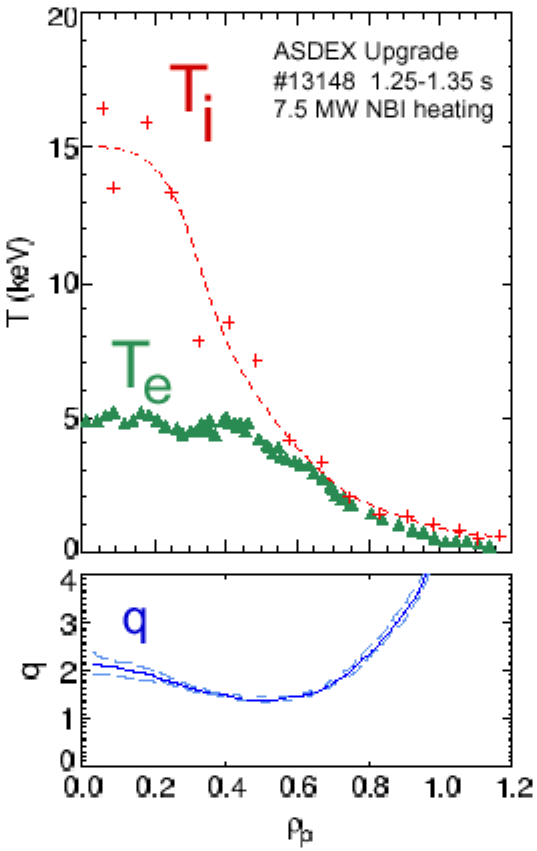
	ITER-baseline	ITER-steady	1st generation reactor designs	"advanced" reactor designs
β_n	1.8	3.1	3.5 - 4	> 4
<β> [%]	2.5	2.9	2.2 - 3	3 - 5

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
$\langle n_e \rangle$ ($10^{19}m^{-3}$)	6.7	7.1	6.5	6.7	5.7
n/n_G	0.82	0.81	0.78	0.82	0.57
$\langle T_i \rangle$ (keV)	12.5	11.6	12.1	12.5	9.3
$\langle T_e \rangle$ (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

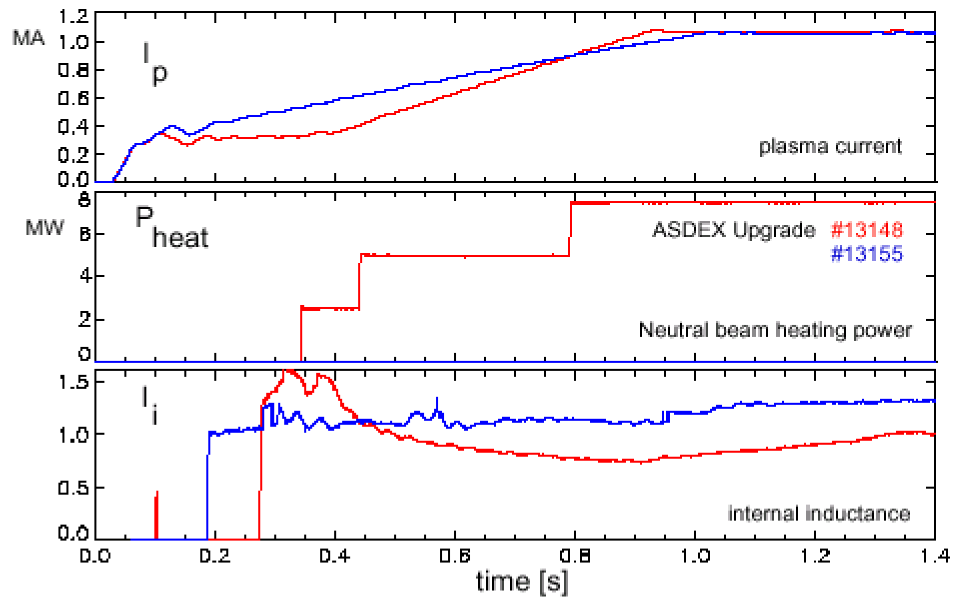
Recent discovery (~1990s): transport barriers in the plasma core



Weak or negative central magnetic shear $S = (r/q)\, dq/dr$

Transport barrier (ions and/or electrons) can develop

Technique: Fast current ramp with heating
$\rightarrow$ skin effect raises edge j



extrapolation and extension of regime

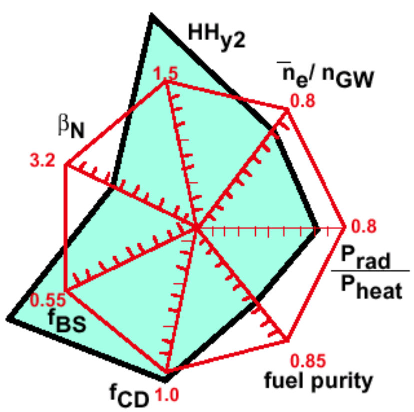
approach to ITER s.s.-targets in dimensionless *performance* parameters:

the 7-fold way*)

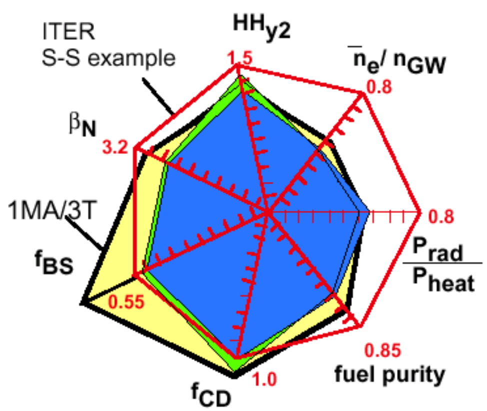
*) + pulse length: -> only full CD,ELMy H-mode cases shown

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

JT-60U RS

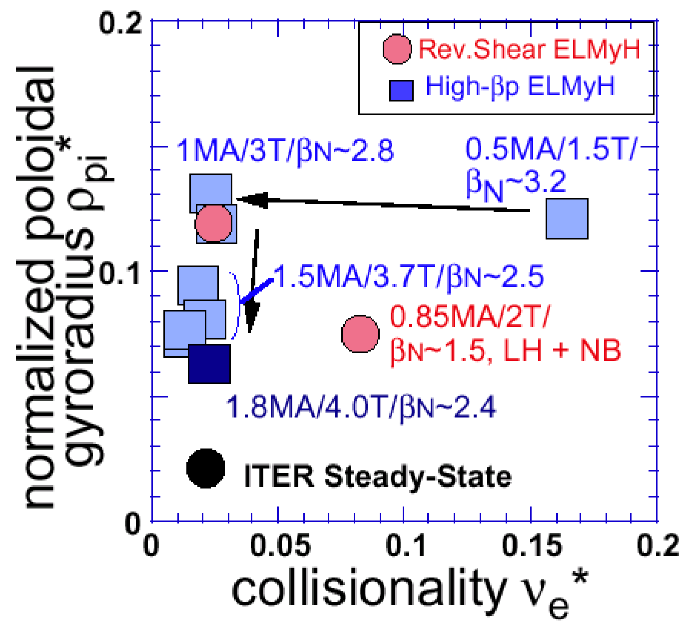


JT-60U high βp



ITER & Power Plant:

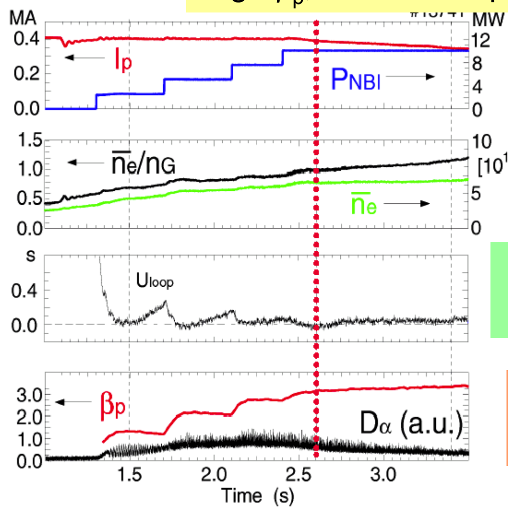
higher n/n_{GW} but lower ν^* !



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

AUG

high β_p, monotonic q- profiles



high n/n_{GW} achieved

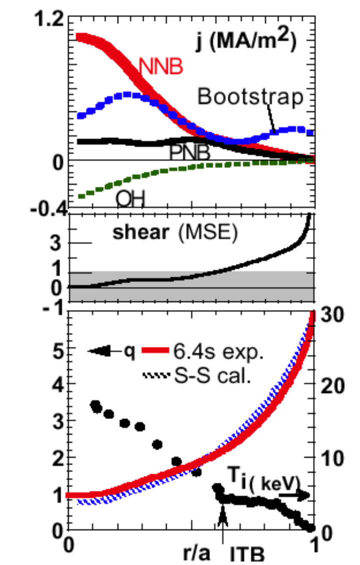
bad bootstrap alignement

good bootstrap alignement

difficult α-particle confinement

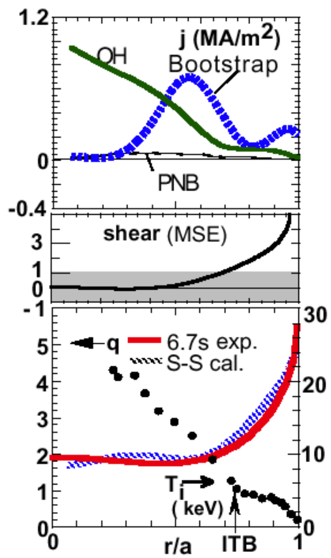
central CD+ bootstrap

q_{95}=4.8, β_N=2.5 HHy2=1.4



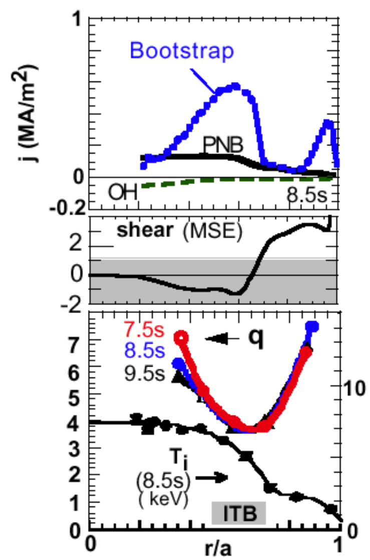
bootstrap

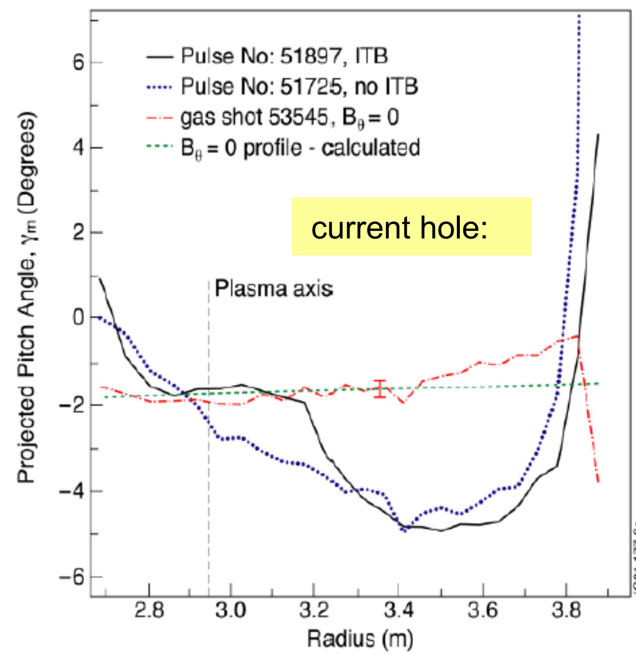
β_N=2.8 HHy2=1.5



broad CD + high bootstrap

q_{95}=9.3, β_N=2.2 HHy2=2.2





JT60-U

JET: LHCD

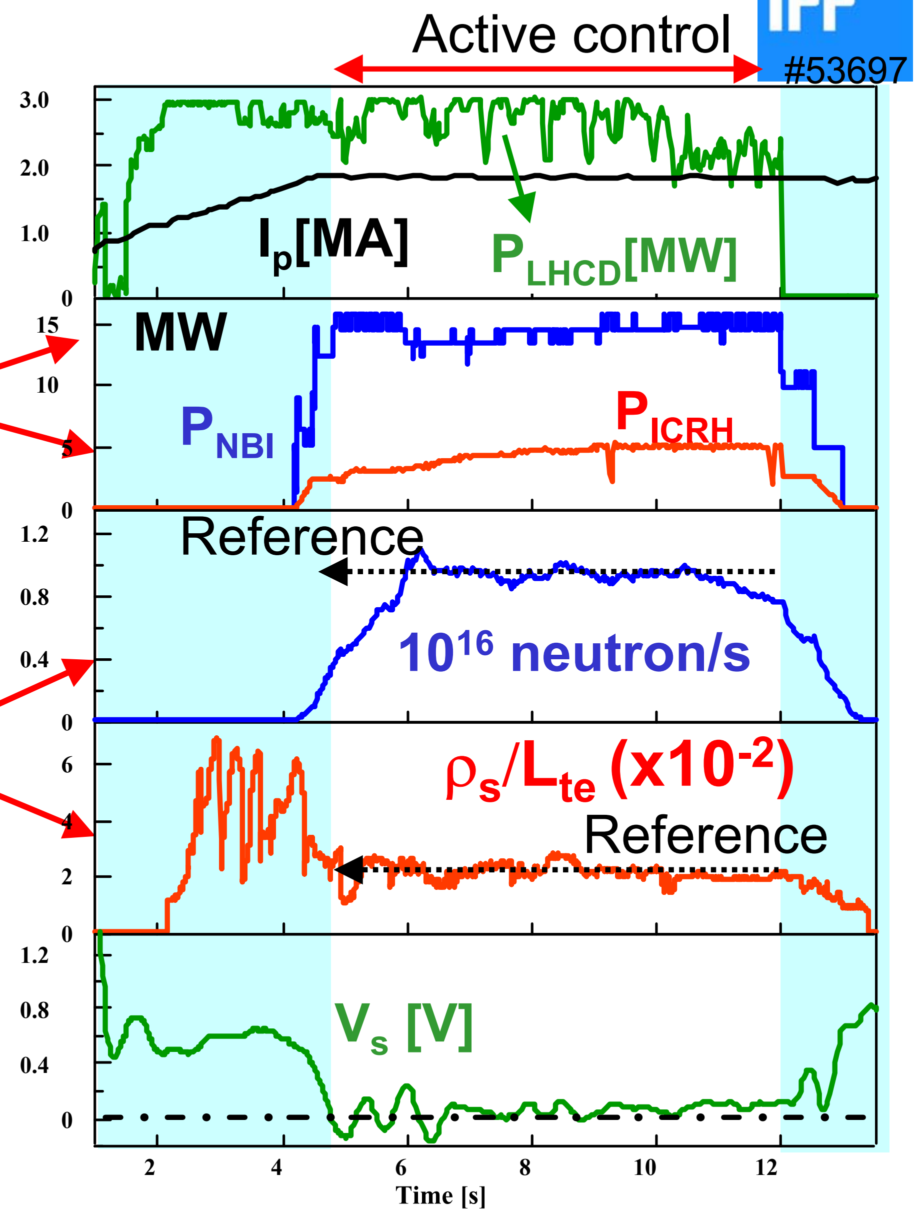
„advanced scenarios“ control

actuators

High non-inductive current fraction reducing current profile development

signals

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



long pulse feedback control of JET ITB discharges

α-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?

pulse length & duty cycle

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

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

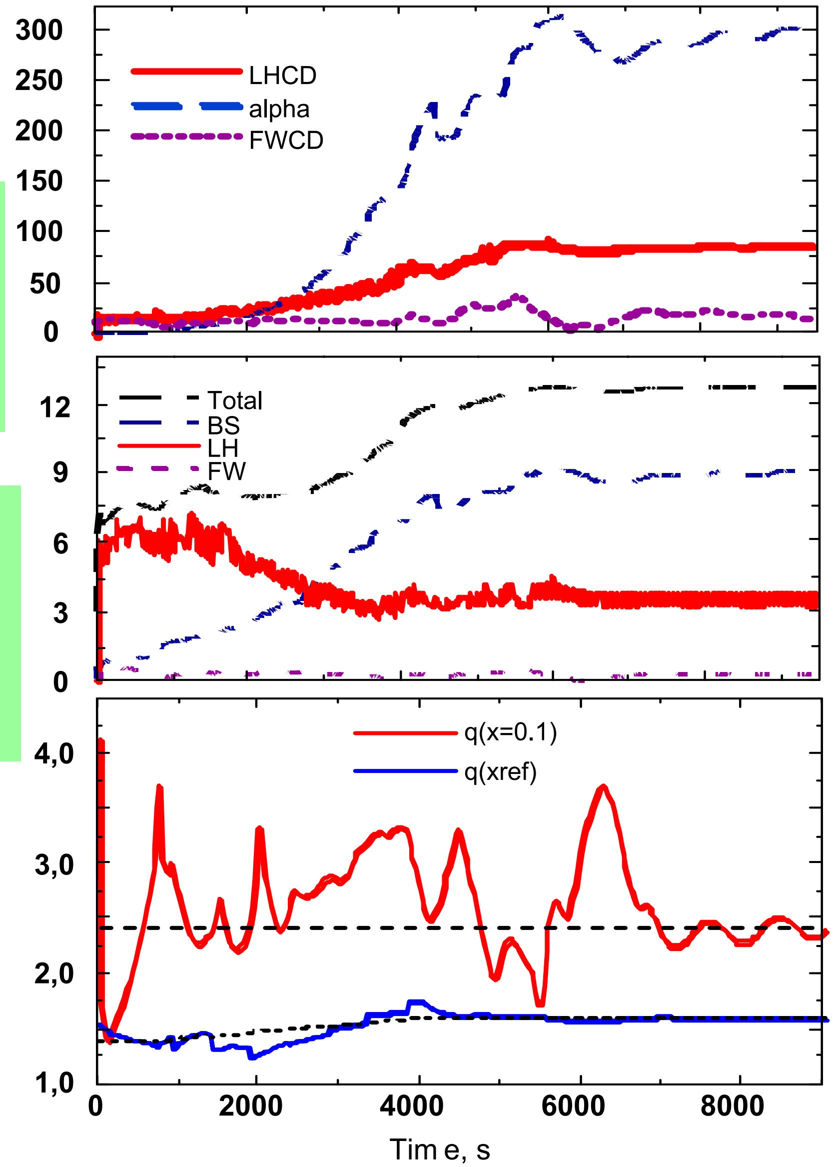
- high availability:

  ⇨ ample time & opportunity for experiments

- (although observation of current diffusion on $\tau \sim \tau_{skin}$)

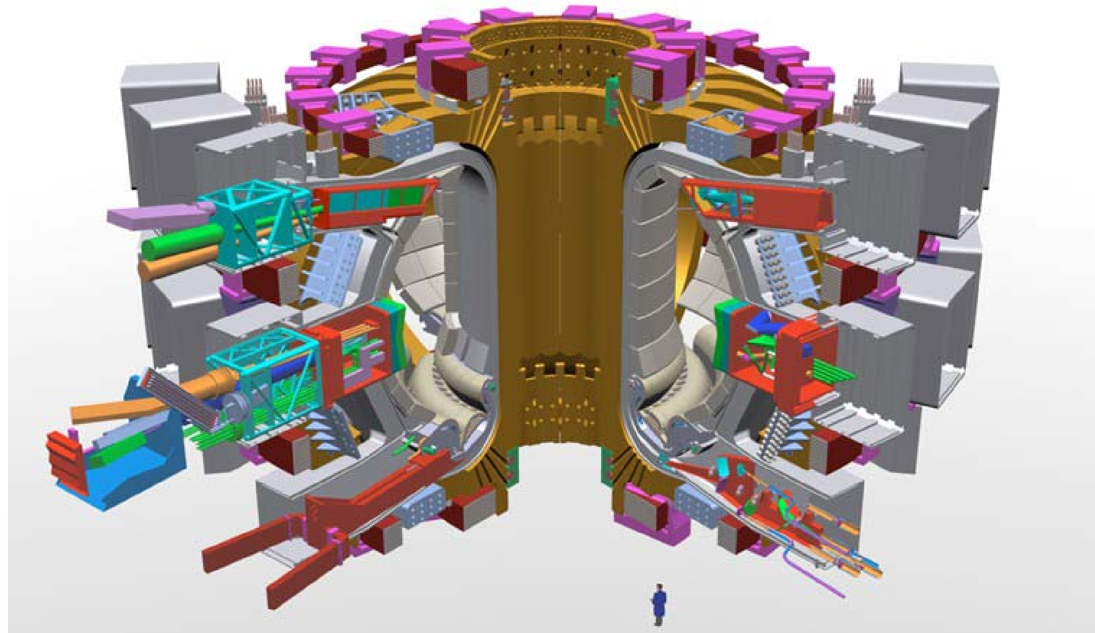
  execution of control:

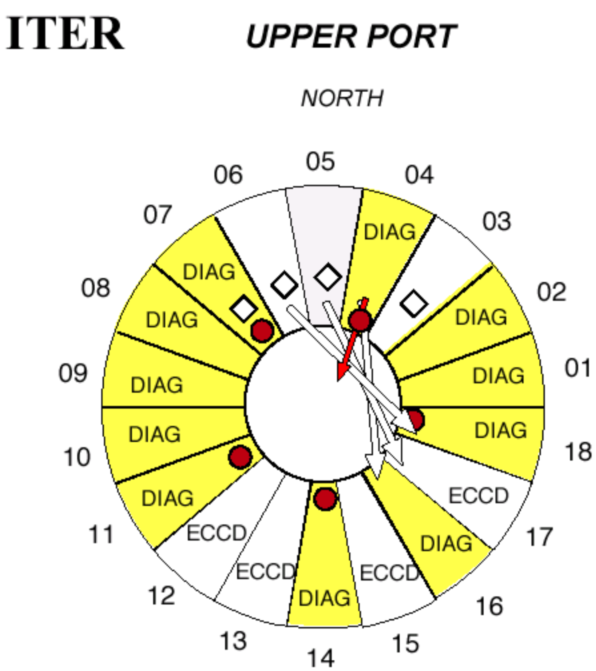
  ⇨ $\tau >> \tau_{skin}$



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

diagnostic access & facilities





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

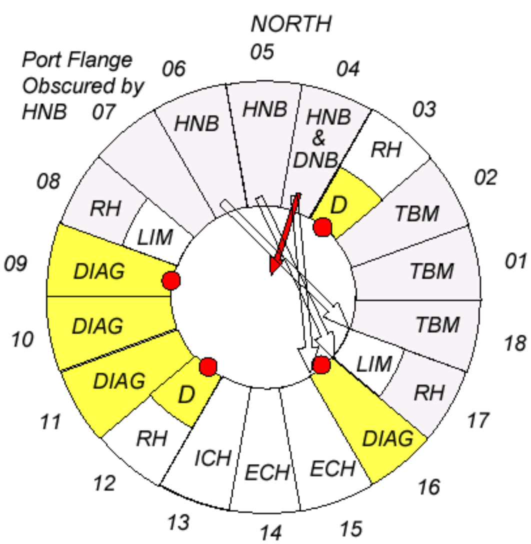
16 Bolometry
   Soft X-Ray
   Divertor Impurity (div16)

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

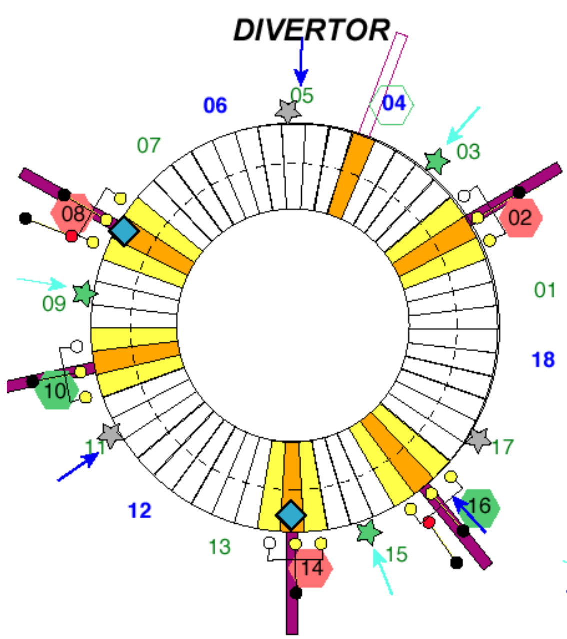
12 Wide angle viewing/IR
H-□ /Vis. spec (upper edge)
Vis. continuum array

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

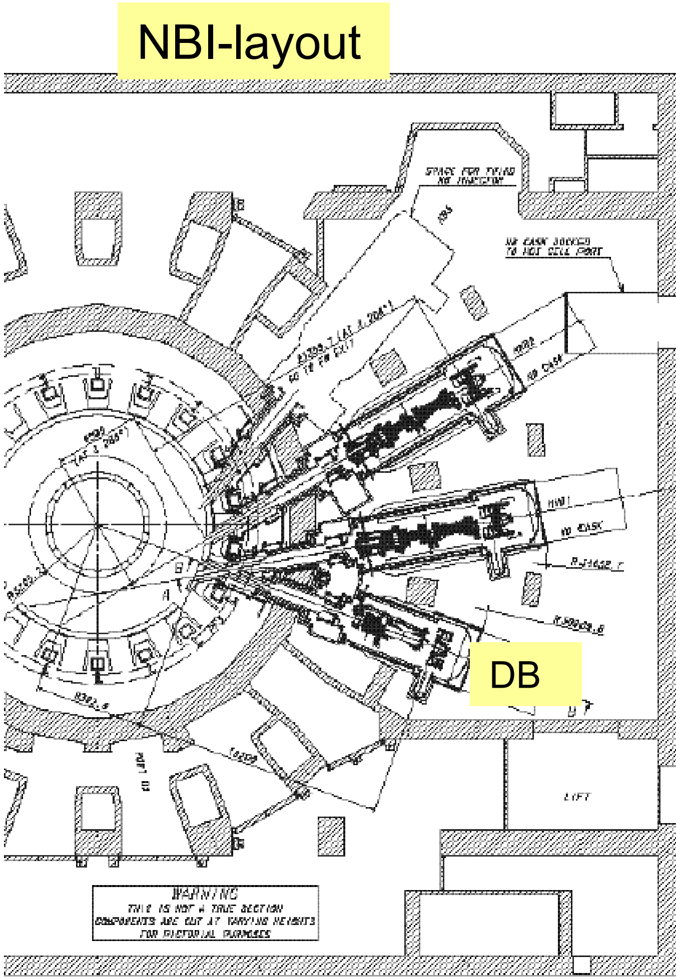
16 Visible Div Impurity Monitor (c,g)
Bolometry, Magnetics
Pressure Gauges,
Thermocouples

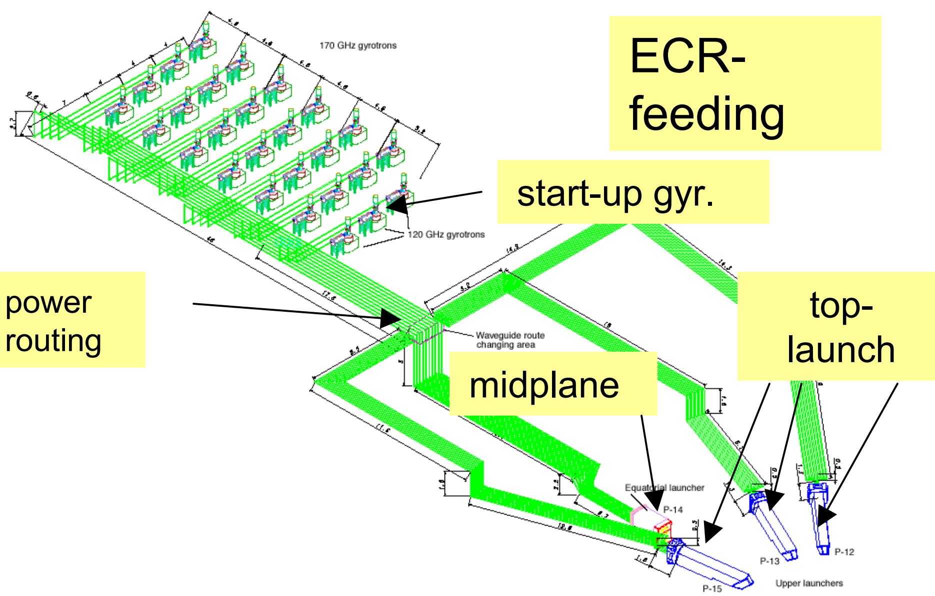
Alloc 7-5-02

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		





heating & current drive systems

heating system	stage I	possible upgrade by	remarks
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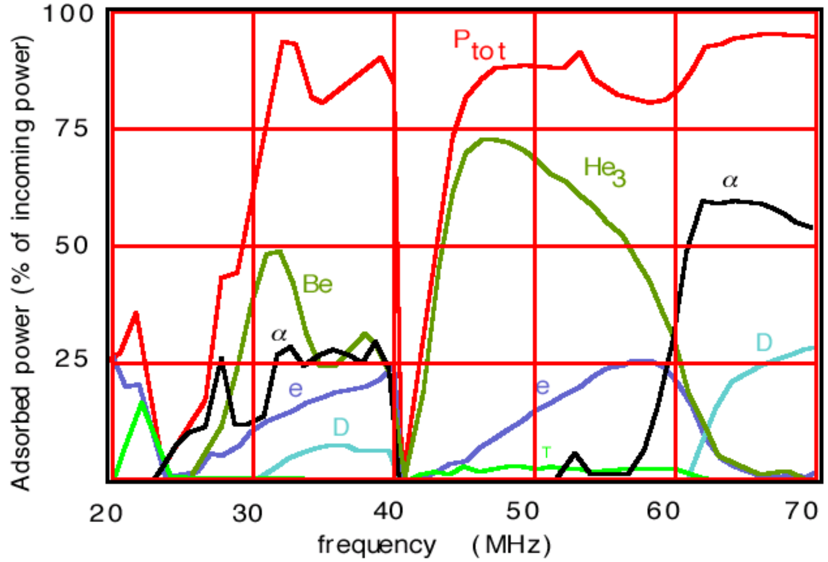
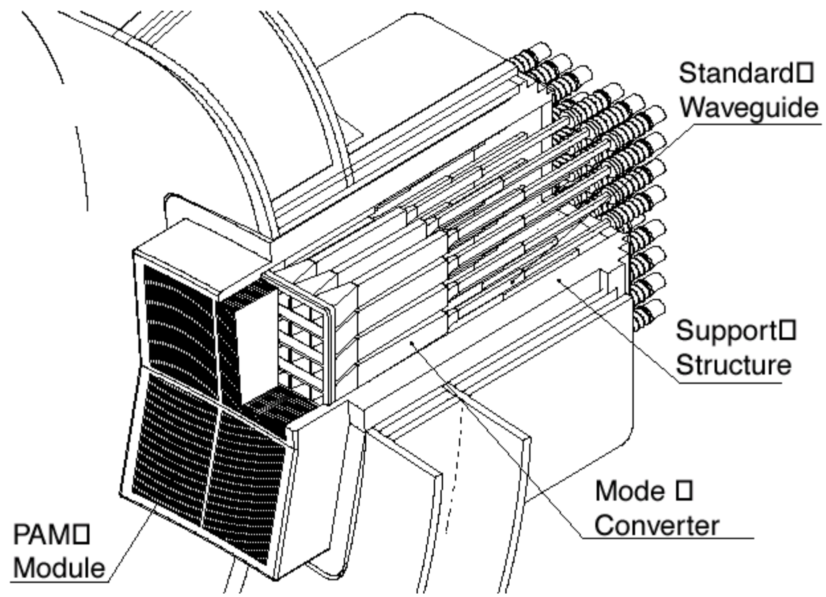
ITER-ω range



IC power absorbtion by species

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

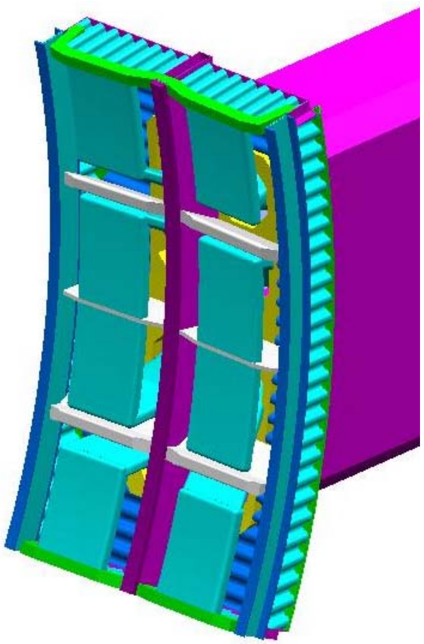
*) to be tested on FTU, Tore-S.



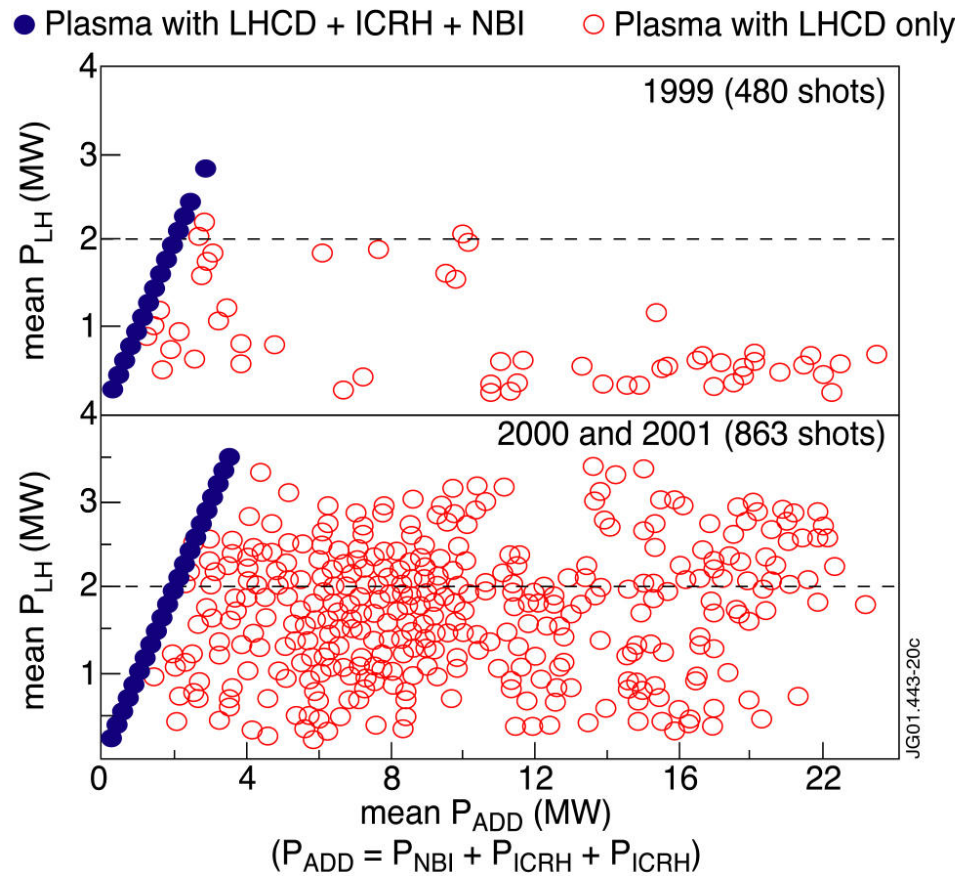
preparatory physics R&D for ITER heating in JET

the JET ICRH ITER-like antenna (2005)

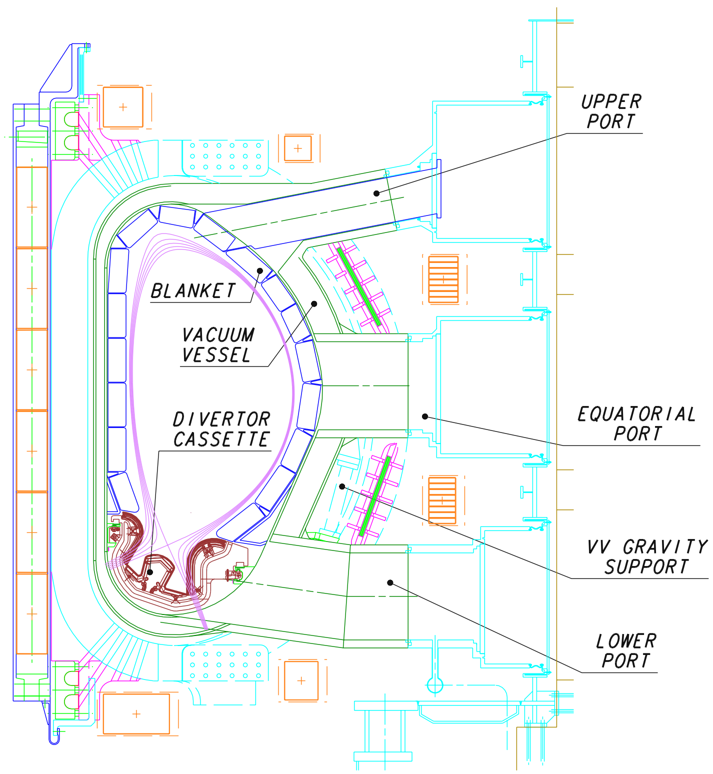
- 7.5 MW at ITER relevant coupling (2-4 W/m)
- High coupling efficiency (90%) in range 30<f<55 MHz
- ELM resilient

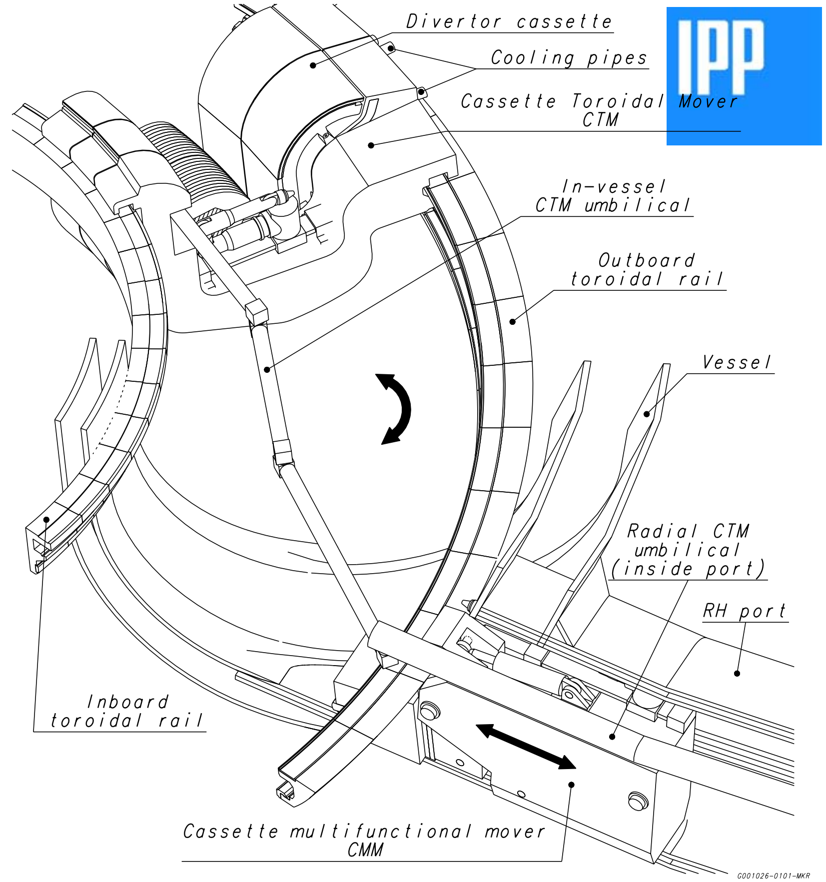


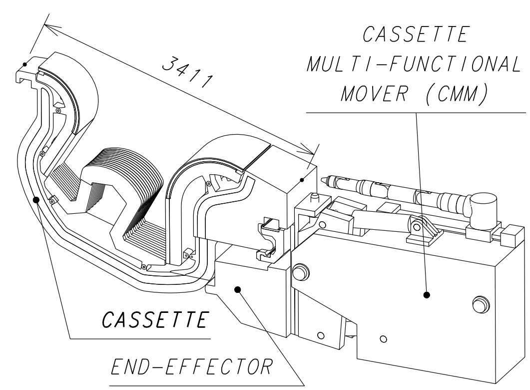
strong effort to increase LH availabilty *in combination with other heating systems*



flexibility through divertor maintanance and exchange capability







for refurbishment and design-improvements

divertor casette system allows replacement of divertor within 6 months:

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

benefit for high-βp ELMy H-mode

inward shift of mass deposition with respect to ablation

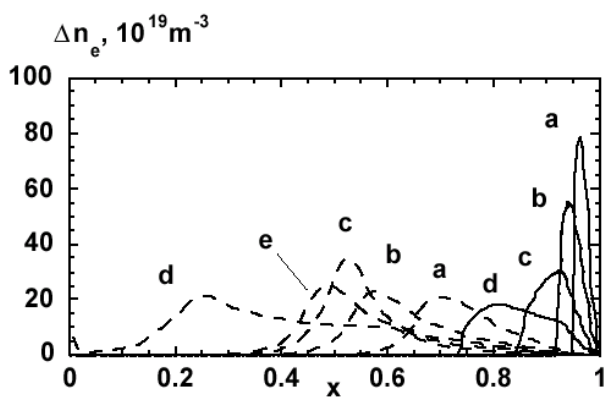
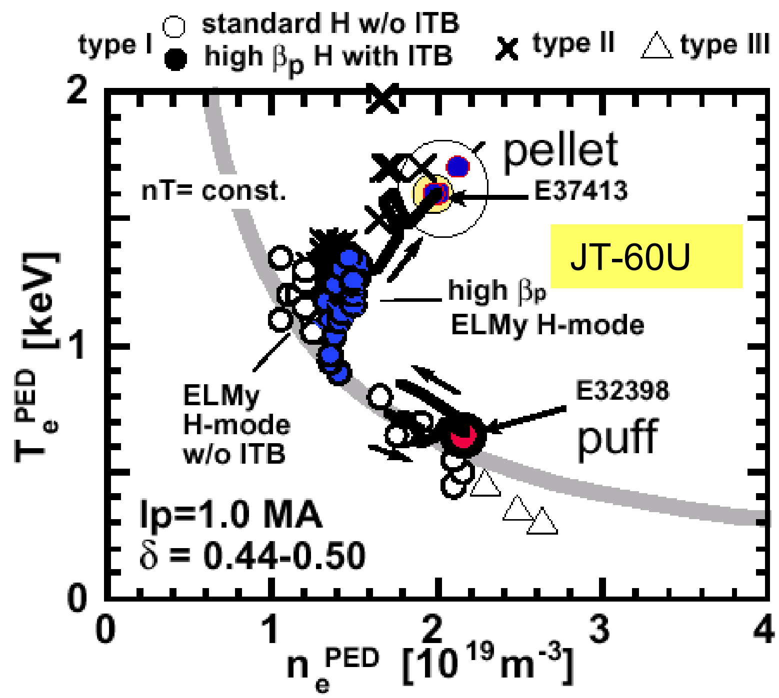
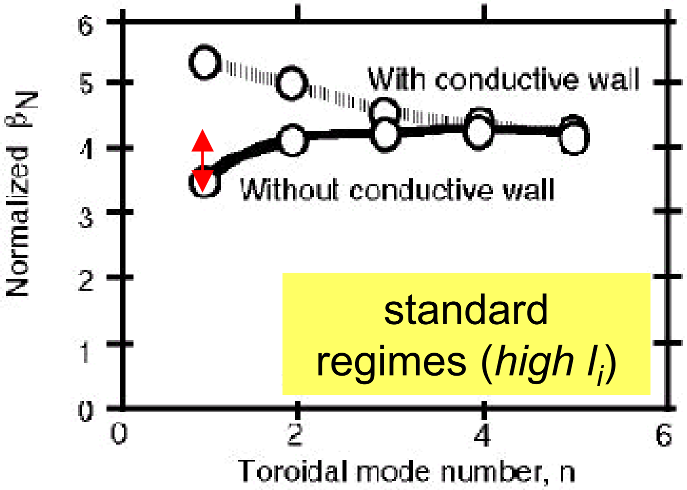


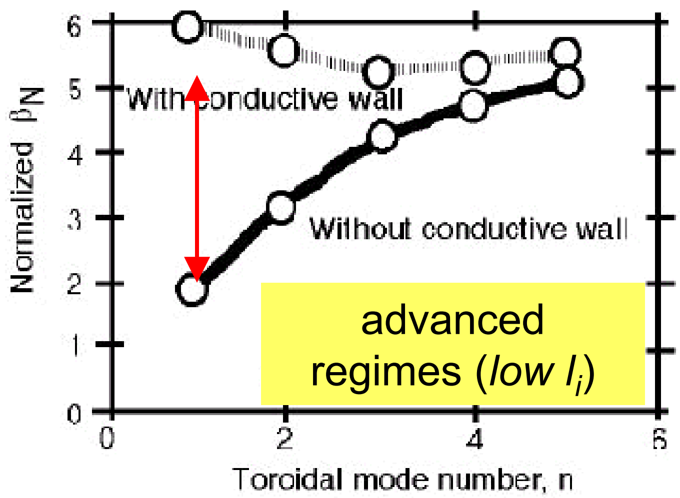
Figure 4.5-2 Model Predictions for the HFS Injection in ITER
Solid lines correspond to pellet ablation, dashed lines for the ablated mass deposition

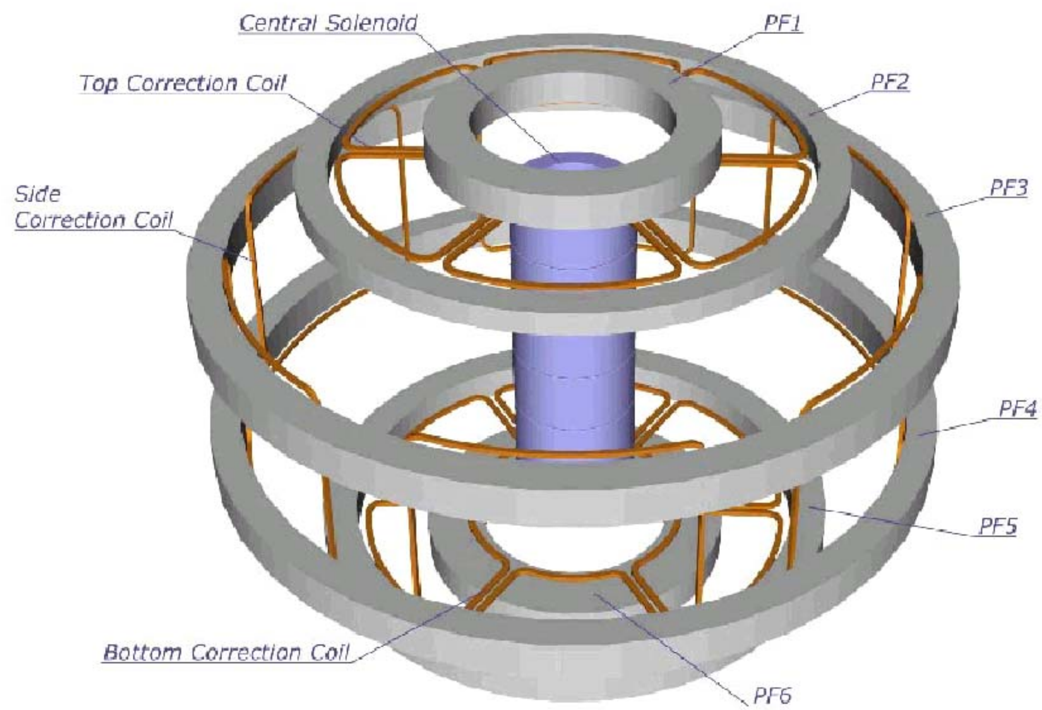


benefit of pellet injection on reverse shear modes: still to be explored

advanced scenarios at high β_n require RW feedback stabilisation







ITER error field correction and RWM control coils

↕ potential gain by low-n RWM feedback

relevant & attractive range of plasma shapes covered:

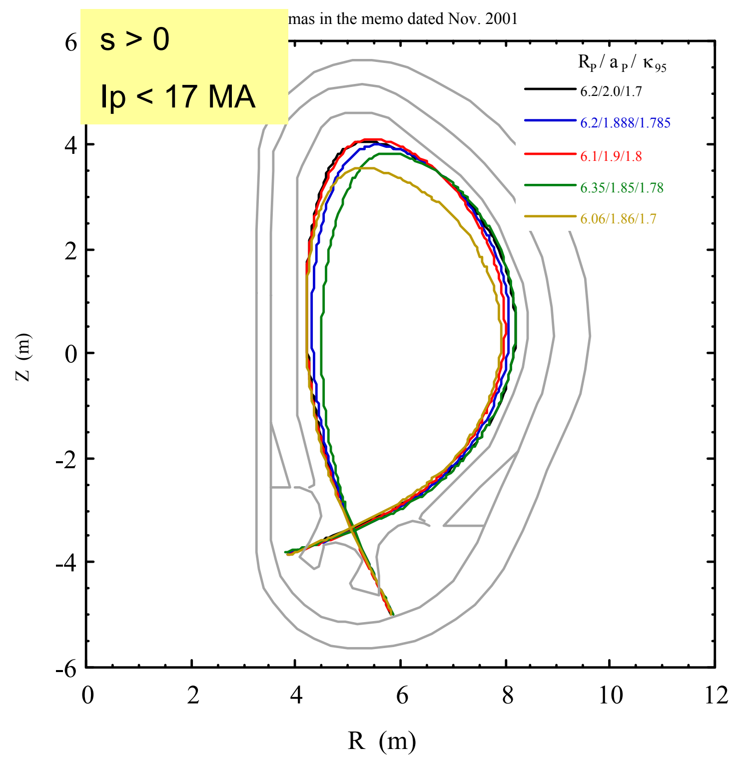
enhanced shaping viz. ITER-FDR

	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

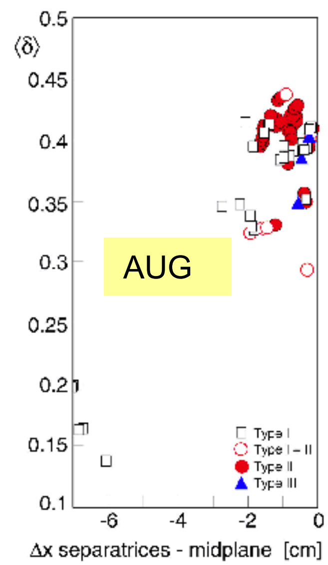
can be further pushed to accomodate important observations

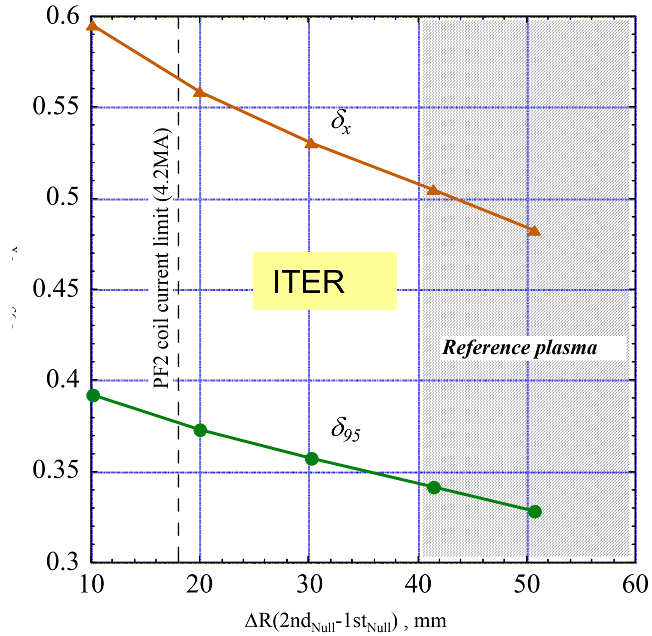
s > 0

Ip < 17 MA



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

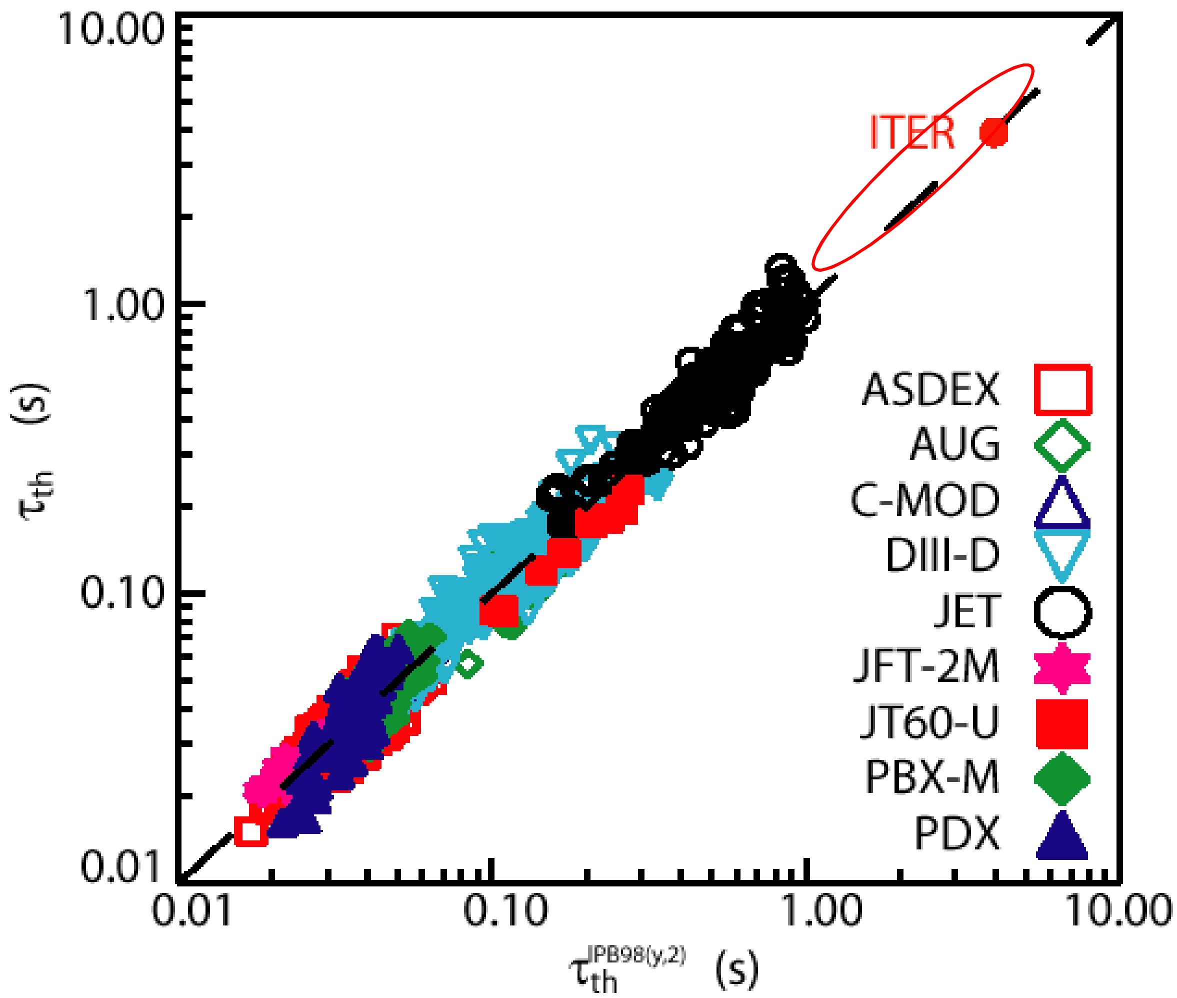




advanced scenarioes - > stronger shaping possible (I_p = 9 MA)

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

ITER´s mission: physics of reactor grade (size) plasmas



ITERis not *one* experiment, but a facility on which we will run a broad range of experiments (like on other devices)

on ITER: no conflict to be expected between

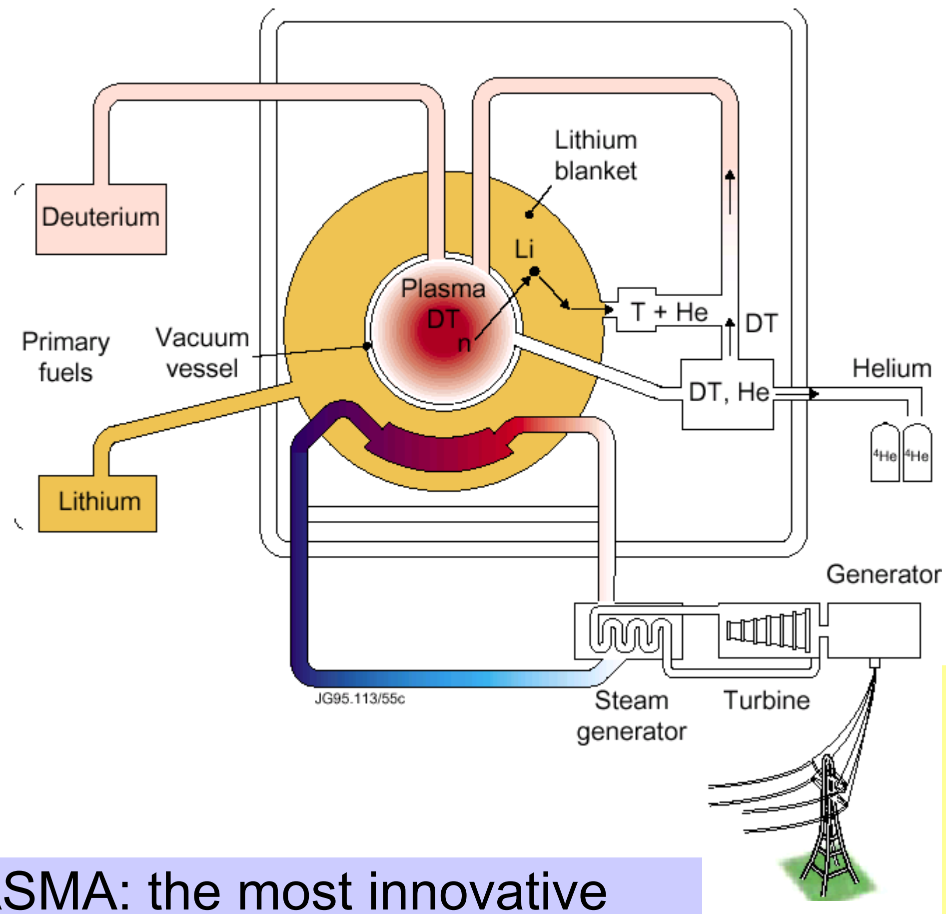
• exciting burning plasma physics

• reactor oriented performance maximization

only high performance plasmas will burn

ITER sufficiently close to reactor that regimes transferrable

Fusion Power Plant: fusion core integrated into a „conventional“ requirement



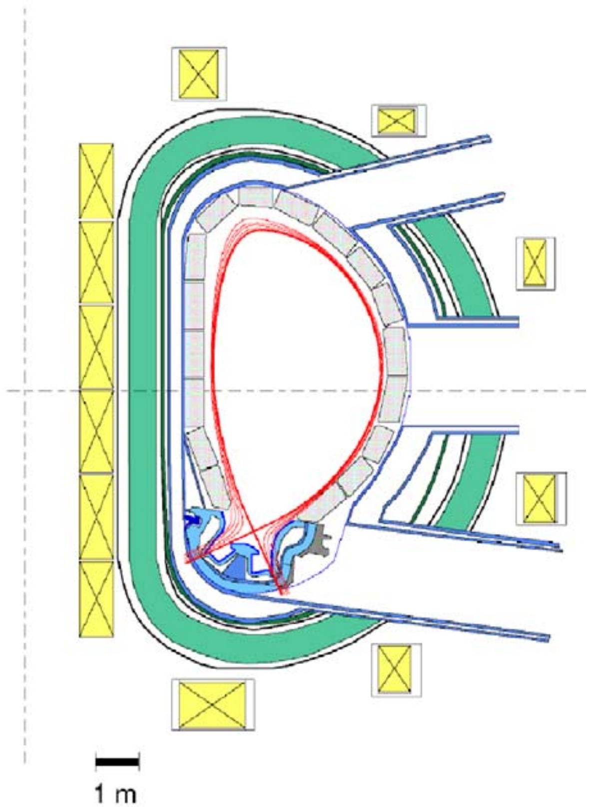
The PLASMA: the most innovative subsystem of a Fusion Power Plant

optimization and control of fusion plasmas

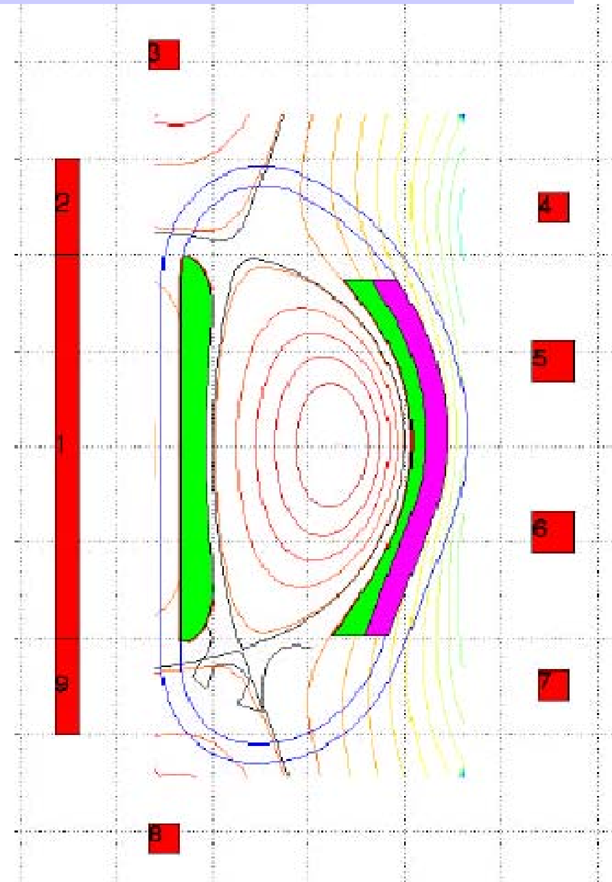
task of ITER and an accompanying physics program

Further Steps to a Power Plant:

physics and materials: the key issues for a fusion power plant



ITER



PPCS-D
(a conceptual power plant)

size and shape of a power plant could be quite close to ITER
(stellarator - sharing most of the physics and technology with a tokamak - might be advantageous for easier steady-state operation)

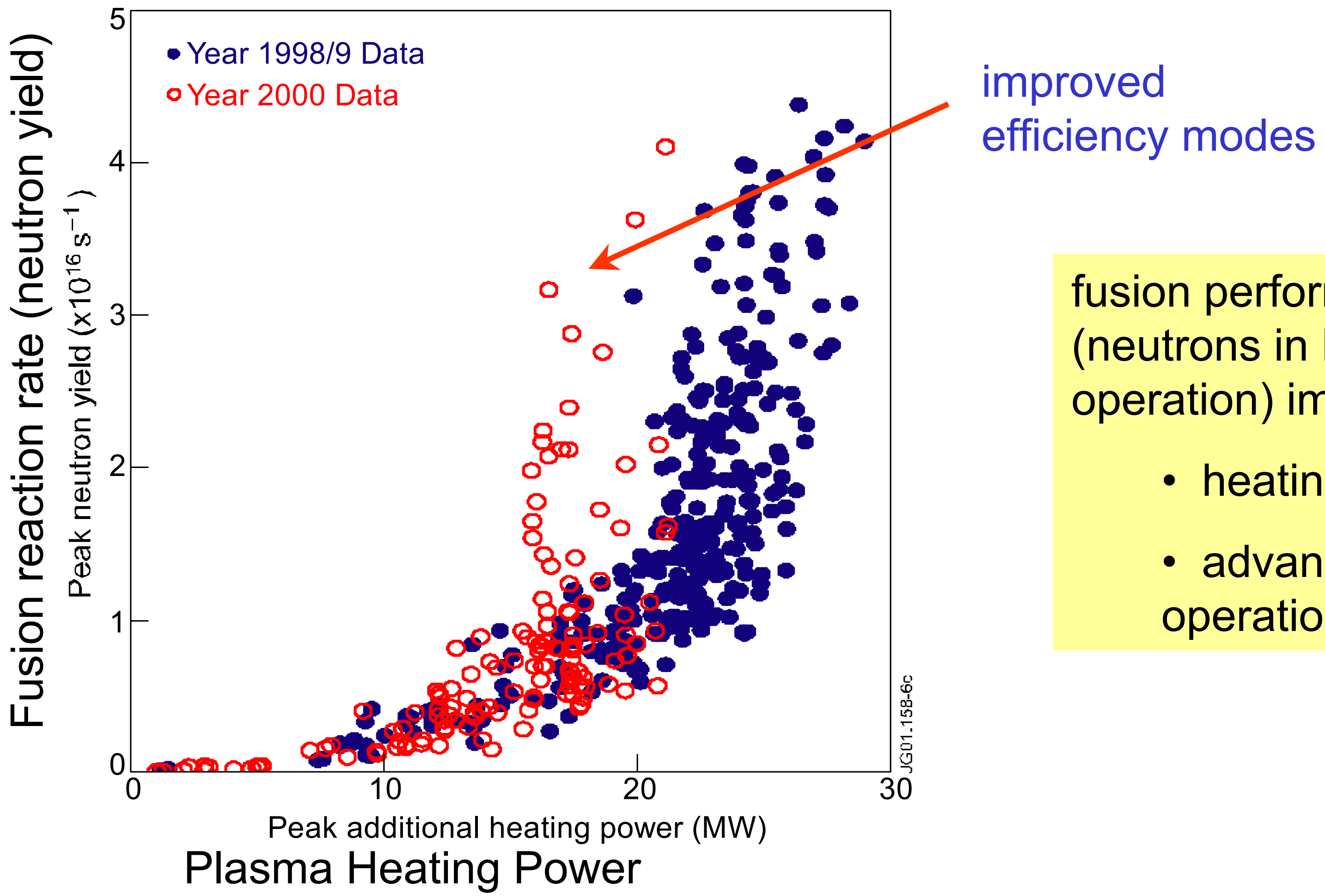
Further Steps to a Power Plant:

Power Plant Conceptual Design Studies:

reactor requirements beyond basic ITER

	ITER	ITER-RS	PPCD - C	PPCD - D
Ro [m]	6,20	6,20	7,5	6,1
Ip[MA]	15,00	9,00	20,1	14,1
fBS	0,15	0,46	0,69	0,76
βN	1,80	2,90	4,0	4,5
H98y	1,00	1,60	1,3	1,2
Pfus [GW]	0,40	0,34	3,4	2,5
Q	10,00	5,70	30	35
Pel, net[GW]	n.a.	n.a.	1,5	1,5
structural materials	SS	SS	Eurofer+SiCSiC inserts;Eurofer ODS for first wall	SiC/SiC
blanket coolant	H_2O	H_2O	He+PbLi	PbLi
breeding blanket	n.a.	n.a.	PbLi	PbLi
design divertor load [MW/m2]	10	10	10	5
thermal power cycle efficiency	n.a.	n.a.	~43%	~59%
<neutron wall load> [MW/m2]	0,5	0,4	2,2	2,4

Further Steps to a Power Plant:
plasma performance beyond ITER nominal requirements



fusion performance (neutrons in DD-operation) improves with

- heating power
- advanced mode operation

Further Steps to a Power Plant:

plasma performance: steady state at high β_N

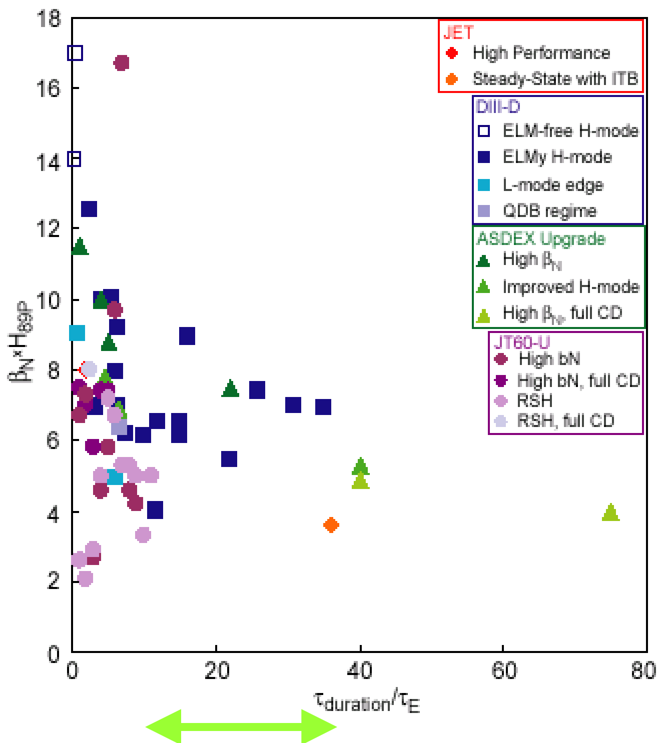
long-pulse control of advanced (high β_N , *H*) regimes

ARIES -AT

PPCD - D

PPCD - A

ITER-FEAT, reference



stationary on τ_E, β_N time scales, but not current profile develop.

attractive reactor regimes so far only attained transiently (in contrast to ITER Q =10 regime)

stationary profile control strongly dependent on heating characteristics

$\Rightarrow$ experiments on ITER critical

Alterantives to tokamak: stellarator ..&..?

up to early 80ies stellarator had no consistent theoretical foundation:

tokamak: axisymmetry ensures a constant of motion -> confined orbits; small neoclassical losses

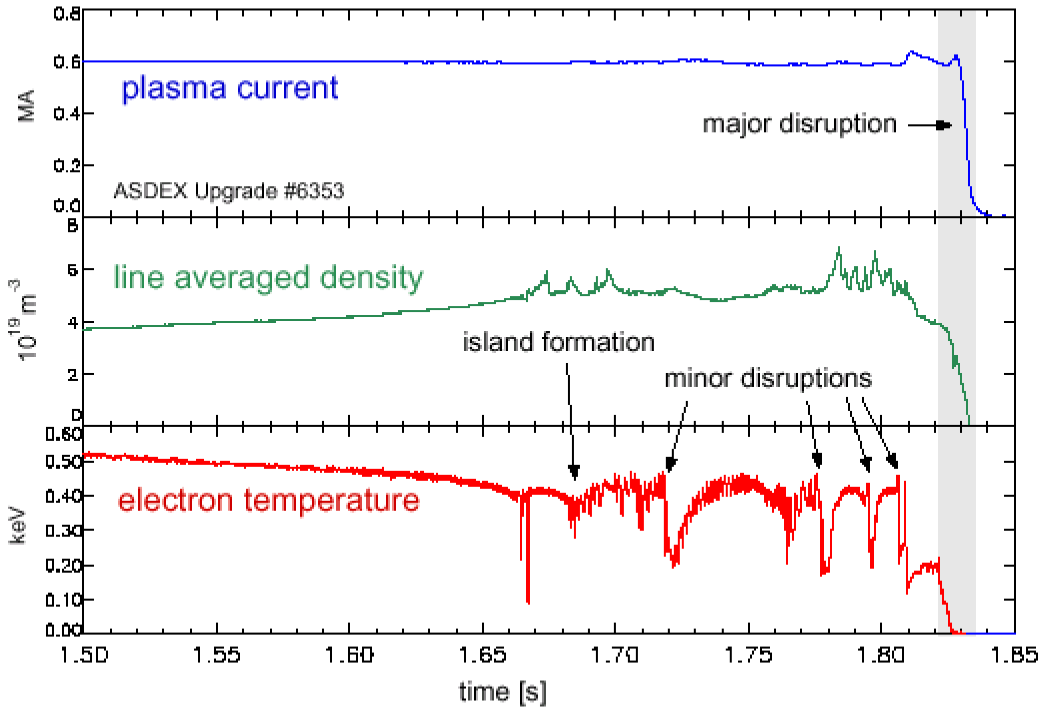
stellarator: discovery of quasisymmetry (Boozer&Nührenberg) configurations exist with constants of motion *in drift approximation*

Alterantives to tokamak: why?

(1) intrinsic steady state capability

(2) possibility of current disruptions

Time history of a (provoked) density limit disruption:



1. Radiation instability
   plasma edge cooled

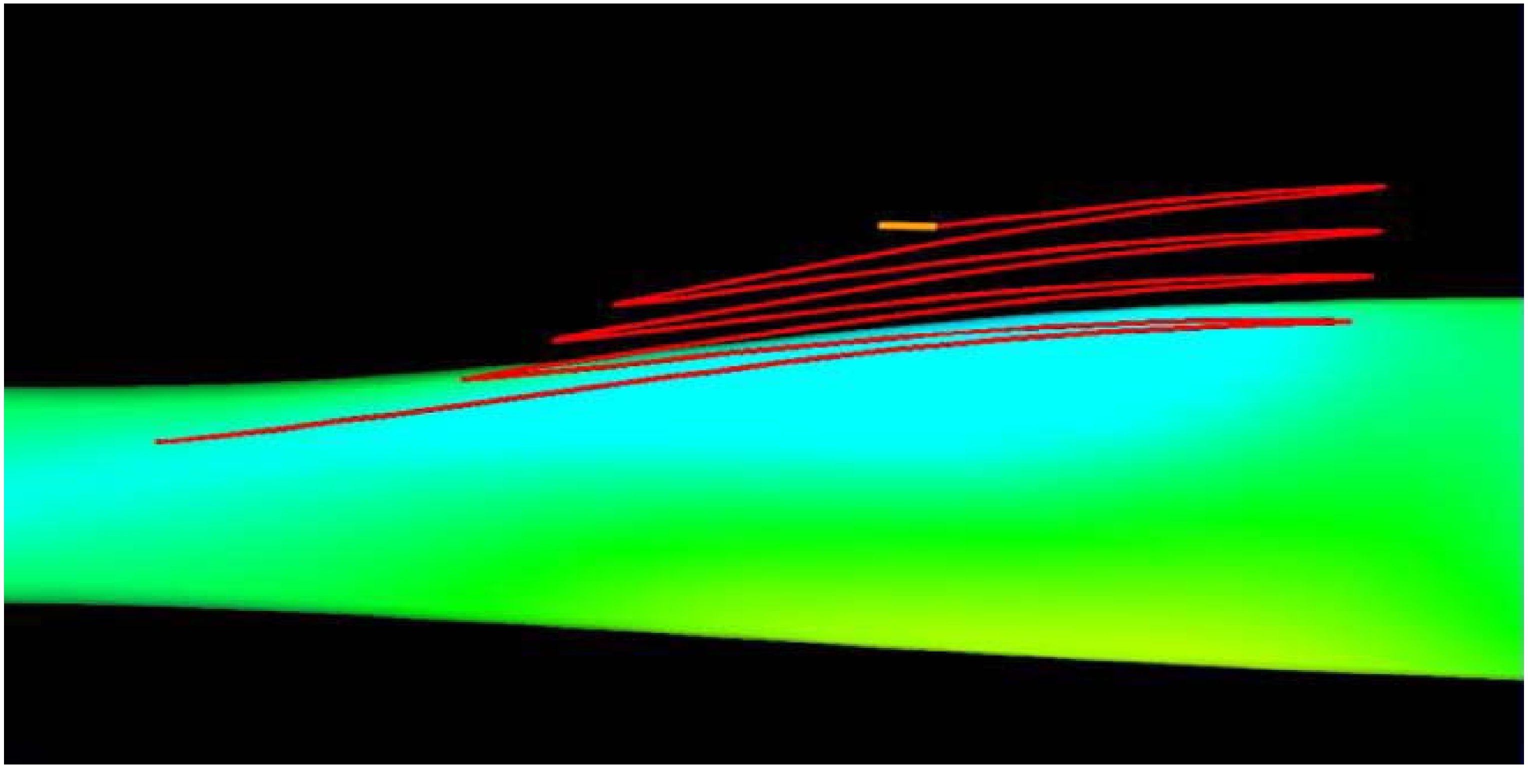
2. Resistive MHD:
   tearing modes
   magnetic islands

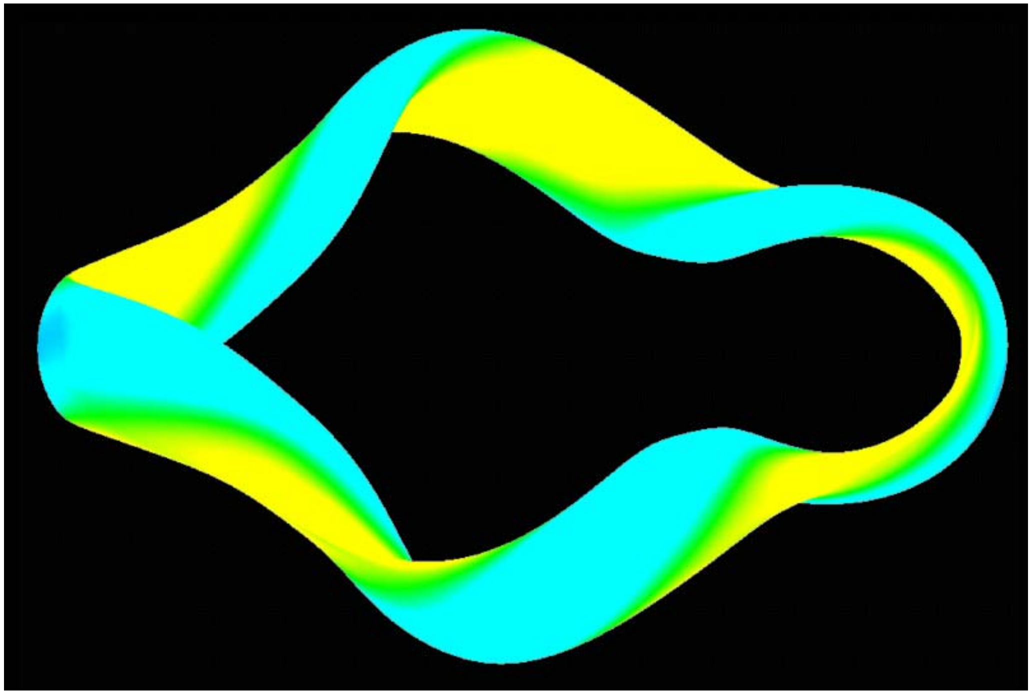
3. "Minor" disruptions
   loss of confinement

4. "Major" disruption:
   plasma current quench

problem of classical stellarator

confinement of fast particles

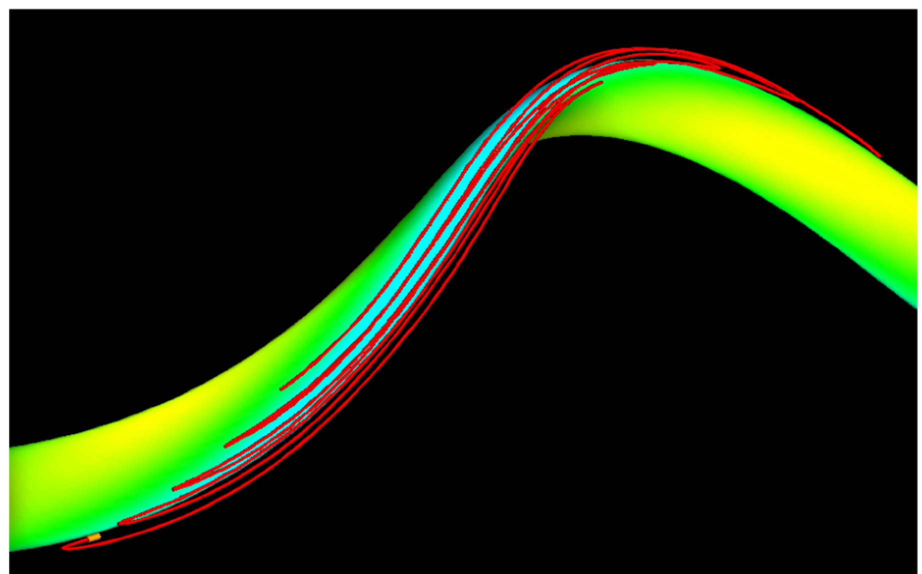




Quasihelikale Symmetrie

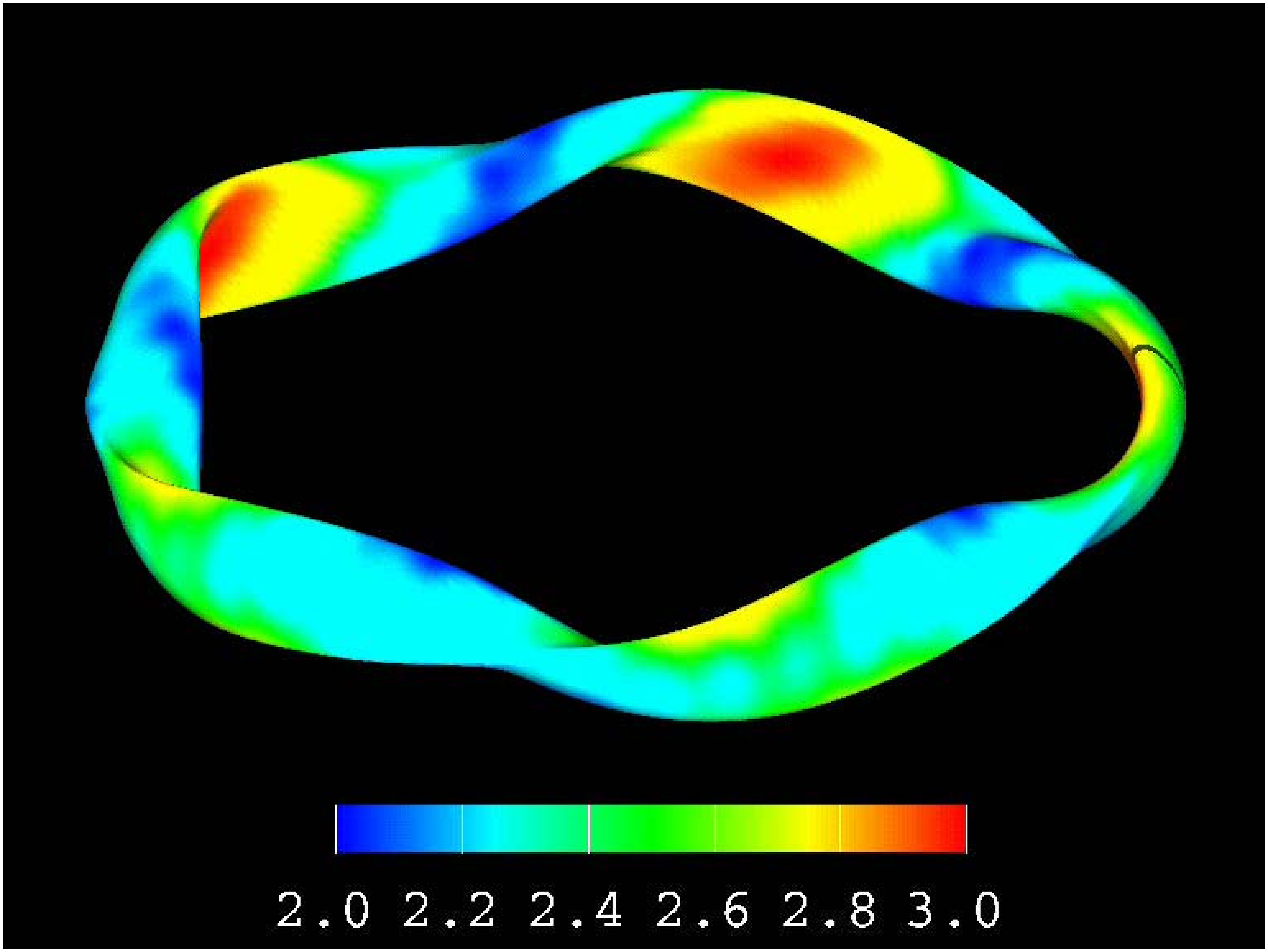
$$B = B(s, \theta - \varphi)$$

gyrocenters rest on
closed surfaces

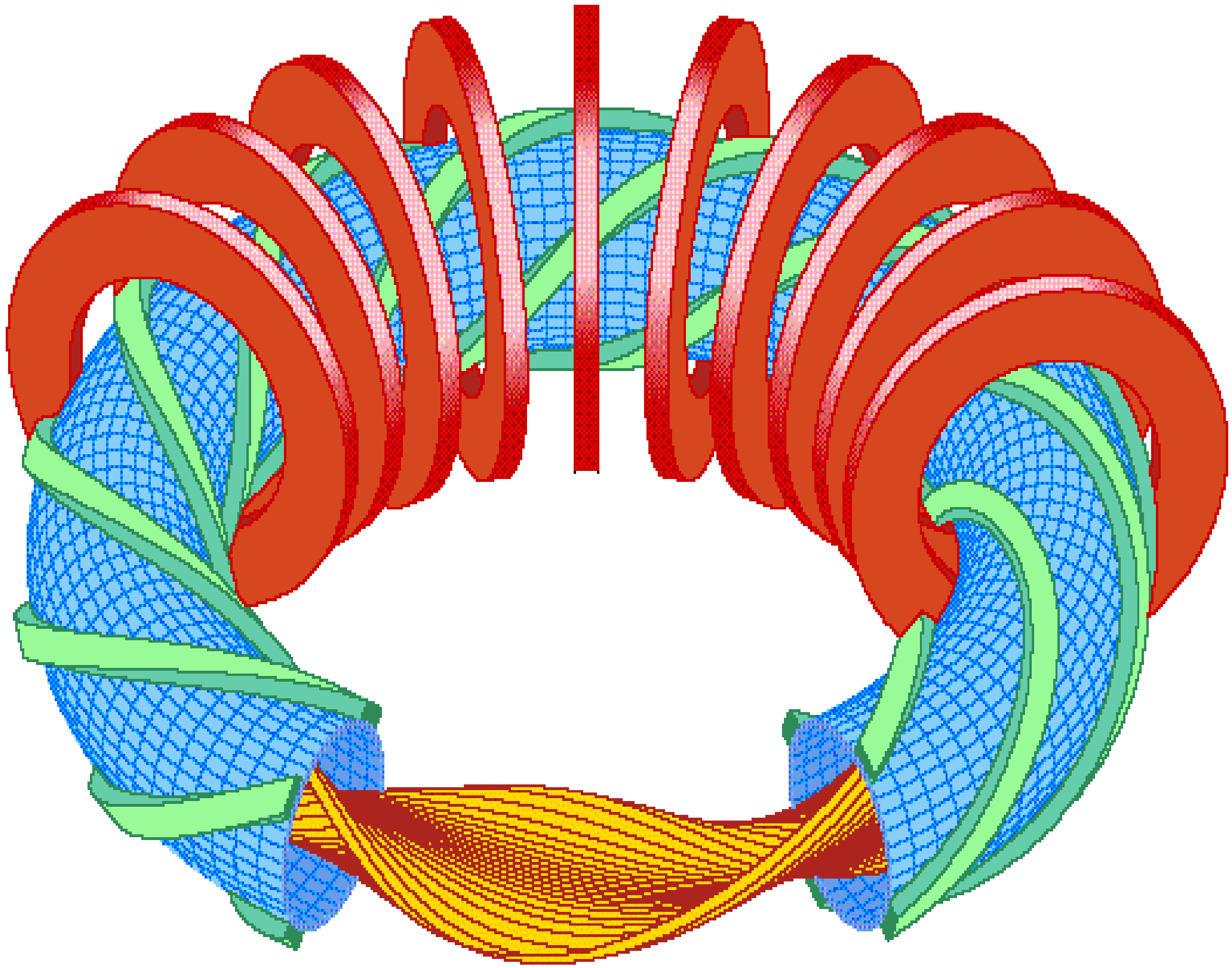


se9913

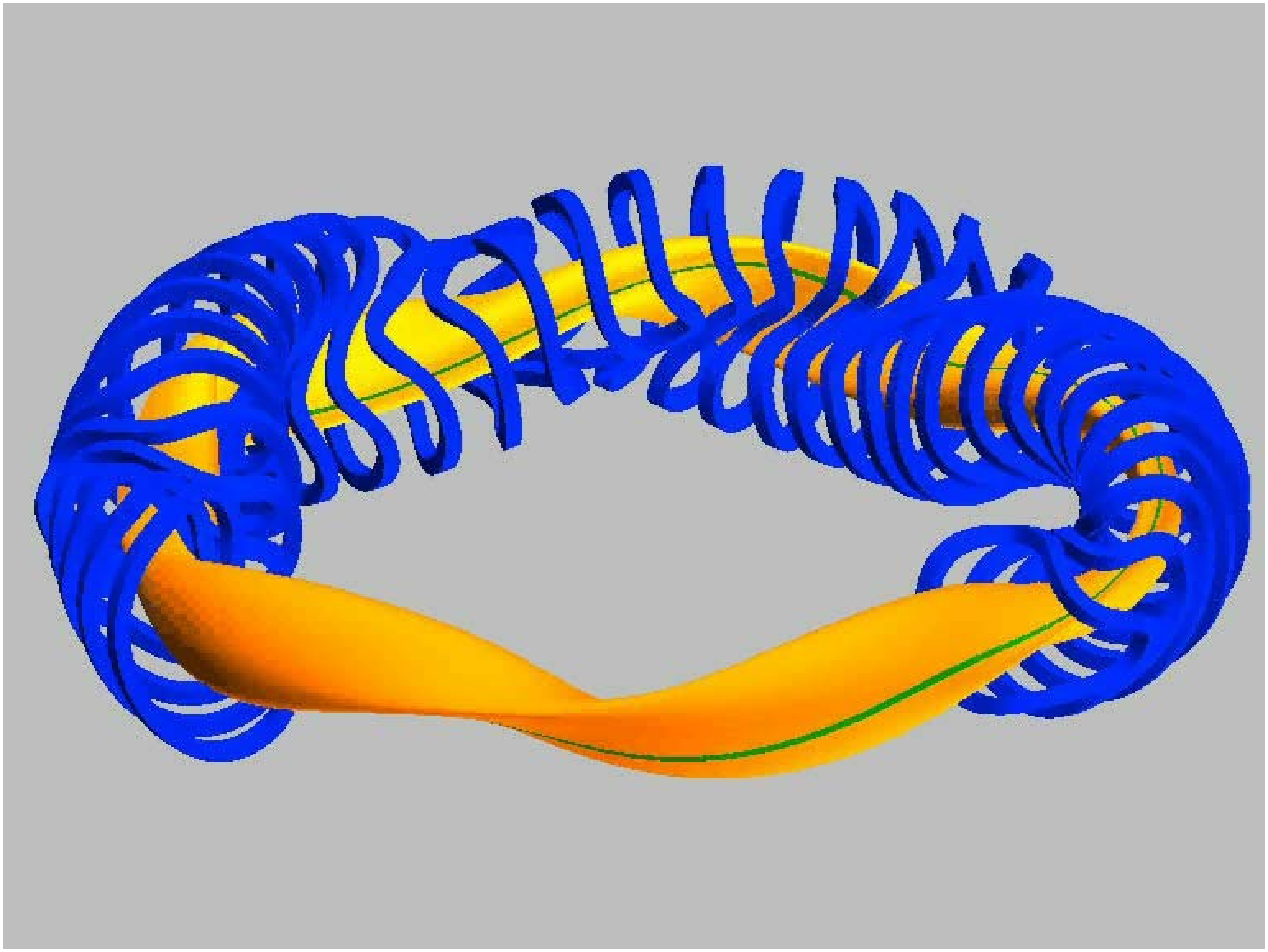
W7-X: confinement of fast particles



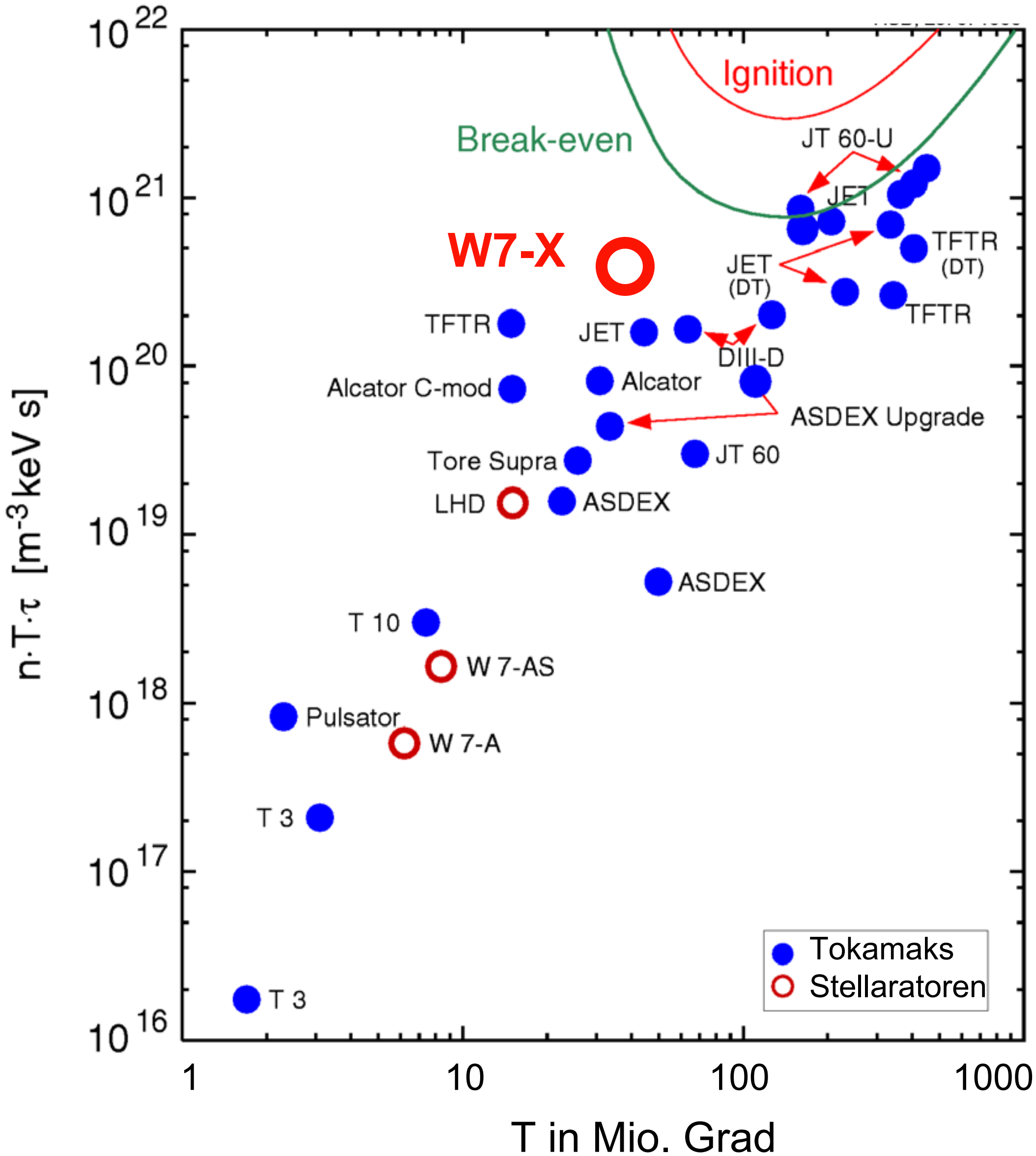
W7-X: modular coils



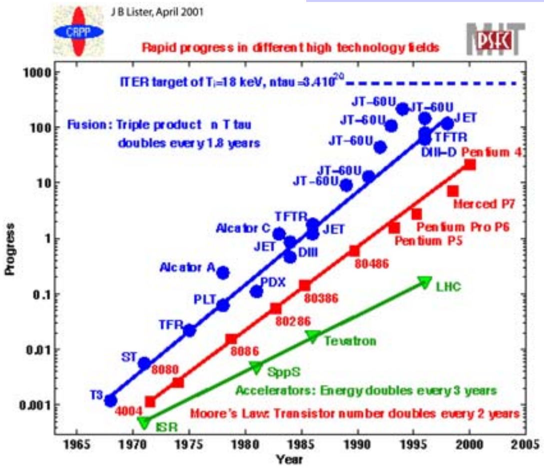
W7-X: modular coils



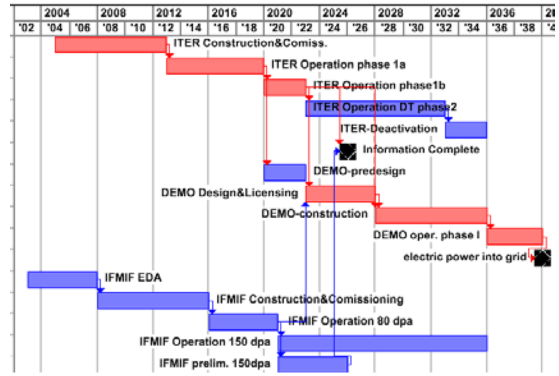
W7-X aim: close performance gap to tokamaks



Summary and Outlook

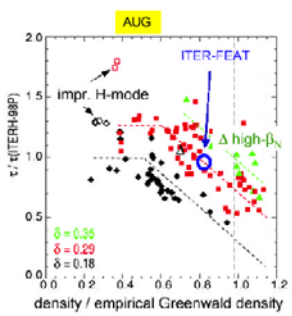


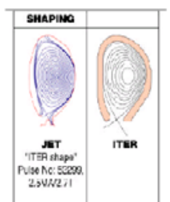
•ITER is the right next step



Preparatory R&D: high confidence level in attainment of Q =10 result of targeted R&D

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

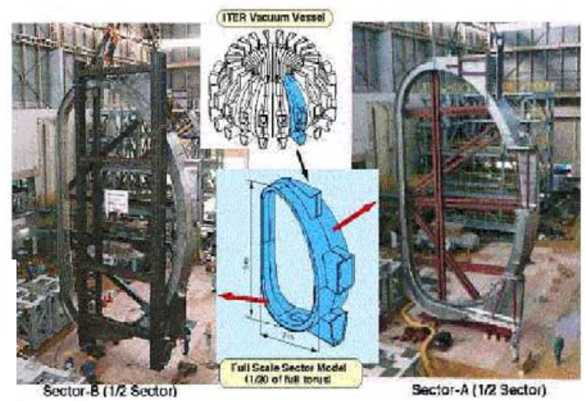




	JET	ITER
$H_{98(y,2)}$	0.91	1.0
β_N	1.90	1.81
n_e/n_{GW}	1.1	0.85
Z_{eff}	1.5	1.7
P_{rad}/P_{tot}	0.40	0.58
κ, δ	1.74, 0.48	1.84, 0.5
q_{95}	3.2	3.0
τ_{pulse}/τ_E	15	110

•its base-line operating mode supported by extensive R&D

Preparatory R&D: Vacuum Vessel (L-3)



•View of full-scale sector model of ITER vacuum vessel completed in September 1997 with dimensional accuracy of ± 3 mm

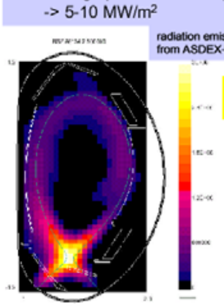
Preparatory R&D: **Physics and technology cannot be separated:**
e.g.: plasma-wall interaction

at plasma-wall contact large heat fluxes

unmitigated -> 60 MW/m²
(comparable to sun surface)

through plasma control (divertor)
-> 5-10 MW/m²

radiation emission from ASDEX-Up



conversion of power flow into radiation:

prototype sustained 2000 cycles of 20 MW/m²

have to be solved in symbiosis of research institutions with industry