ITER
Opportunities of Burning Plasma Studies

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28th EPS
June 18-22, 2000
Madeira, Portugal

The technical requirements for the new ITER

1) Demonstrate $Q \geq 10$ for 300-500 s, do not preclude $Q \sim \infty$.

2) Aim at demonstrating steady-state at $Q \geq 5$

3) Demonstrate availability and integration of essential fusion technologies, and

4) Test components for a future reactor including blankets (> 0.5 MW/m^2, > 0.3 $MW \cdot a/m^2$.)

ITER is planned to be the first fusion experimental reactor.

— Flexibility is required to

1) cope with uncertainties,

2) study/optimize burning plasma for various objectives, and

3) introduce advanced features

— ITER operation should

1) involve the world-wide fusion community

2) promote scientific competition among the Parties

3) encourage mobility between ITER and domestic programmes

Issues of Burning Plasma

Reactor Development: Stable fusion power production with

High Normalized Beta (β_N) :	> 3 in SSR, > 2.5 in PR
High Bootstrap Current (I_{BS}) :	> 60 % in SSR
Low Divertor Heat Load:	< 10 ~ 20 %
Avoidance of Disruption	

Burning Plasma Physics

Collective effects of fast alpha particles

$\beta_{f\alpha}$ and other profiles

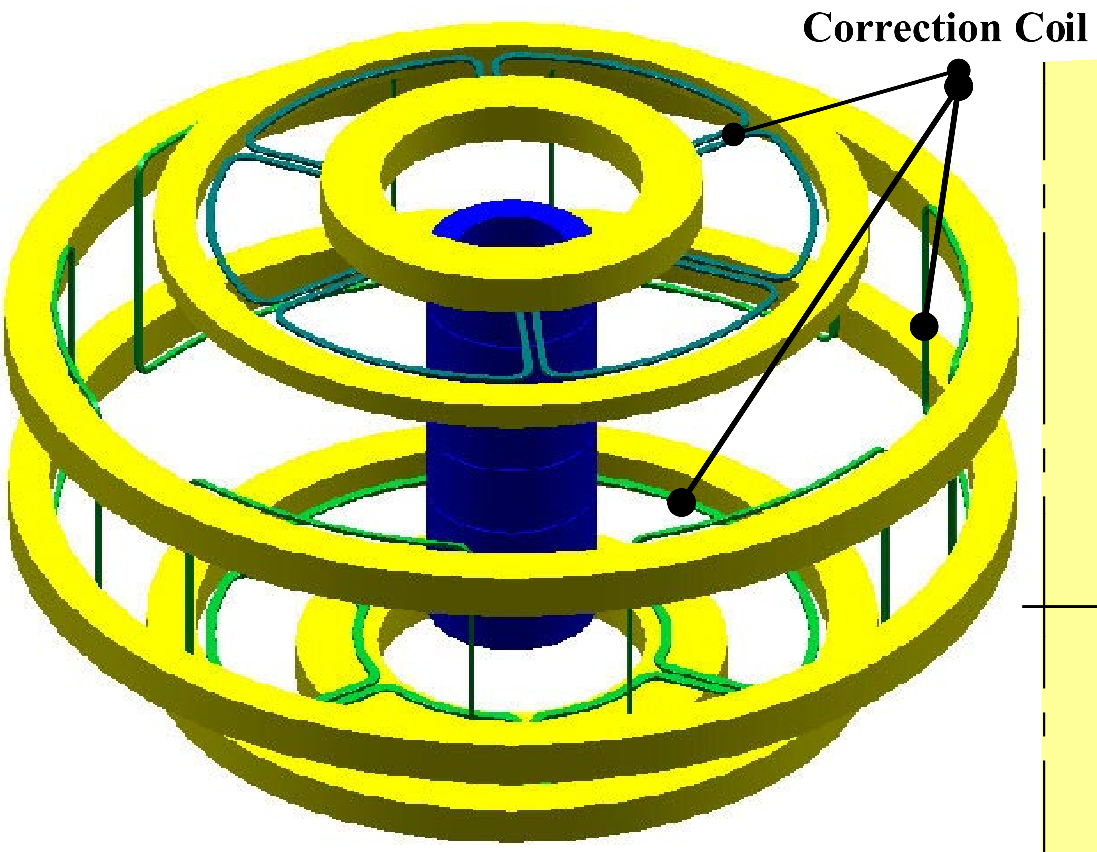
Self-heating$\rightarrow$ thermal stability, self organization,

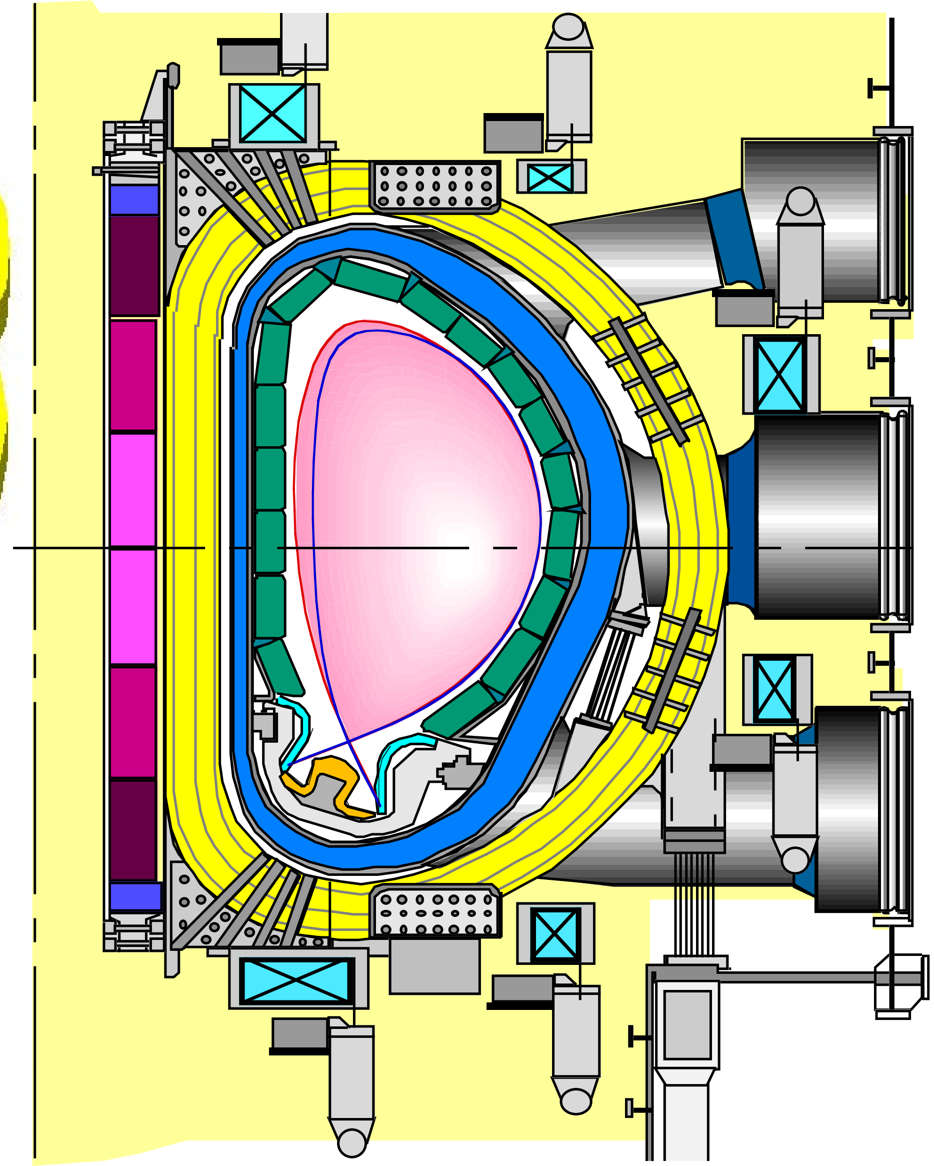
Q,

Interaction among pressure, current, self heating, transport ..

Reactor Scale Physics

TAEs, disruptions, pumping and fuelling, beta, density, confinement, core-edge integration .





ITER Poloidal Field Coils

Correction Coils
6x3, 100-150kA/coil
For Resistive Wall Mode
~10G/20kA

Shot Number : ≥ 30,000 with nominal condition,   Duty Factor : ≤ 25 % or 440 s burn/1800 s

Divertor with Long Legs (~1.1 m)

Particle Exhaust

Divertor with long legs (> 1m) and large pumps (200 Pam^3/s, 200 m^3/s, 10 s)

$F_{core} < N/\tau_E \sim 2.5 \times 10^{22}$/s~50Pam^3/s, $F_{divertor} \sim 2 \times 10^{24}$/s ~ 4000 Pam^3/s

Detachment is not a necessary condition.

Heat Exhaust

Plasma flow to divertor target < 60 MW/6m^2

The present design 20 MW/m^2, CFC or W

Very high radiation cooling and detachment are not necessary conditions.

but will have to be studies for reactor plasmas.

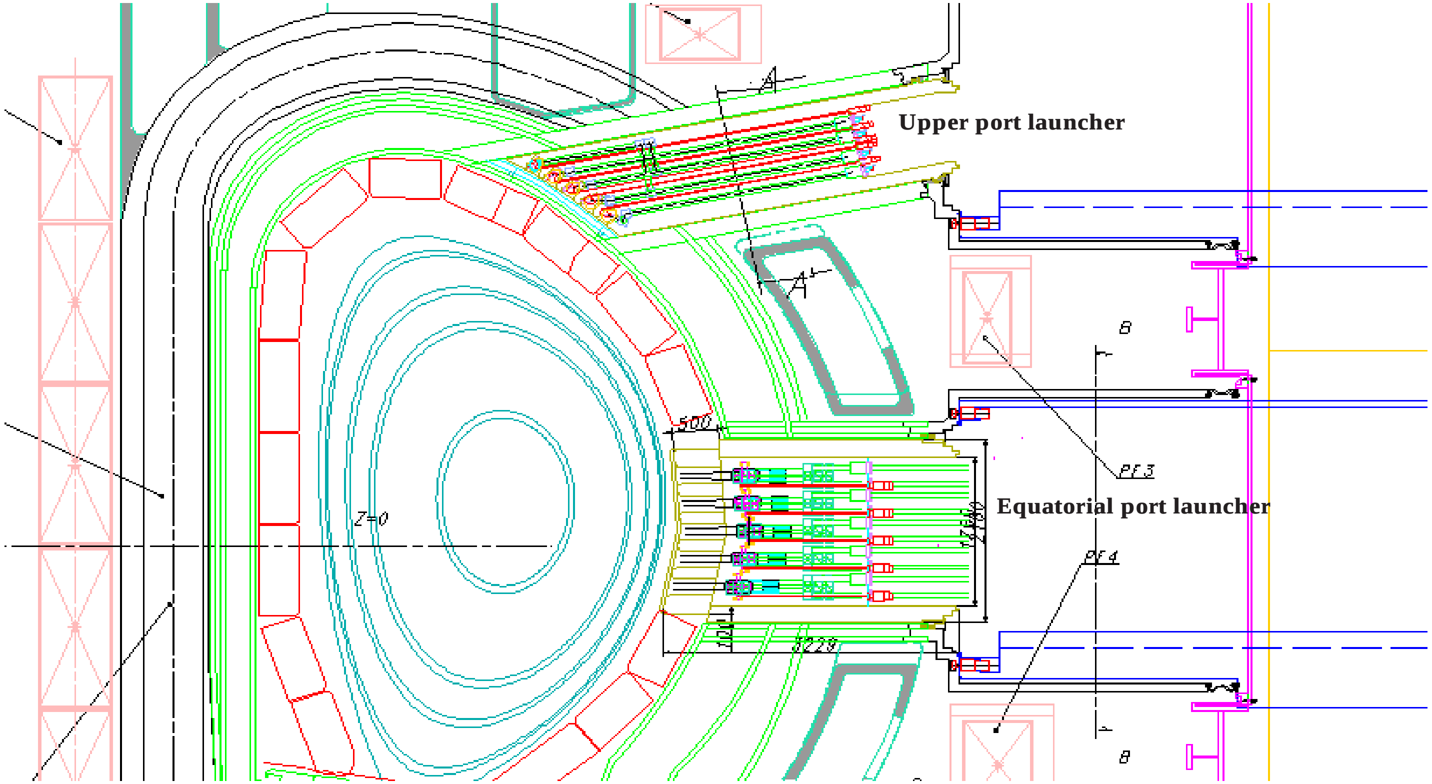
Divertor target material CFC (or W)

Early phase CFC because of its compatibility with disruptions

Later phase W because of its longer life time for normal erosion

High fluence Test : long pulse q_{95} >3.5 operations with small ELMs

Electron Cyclotron System



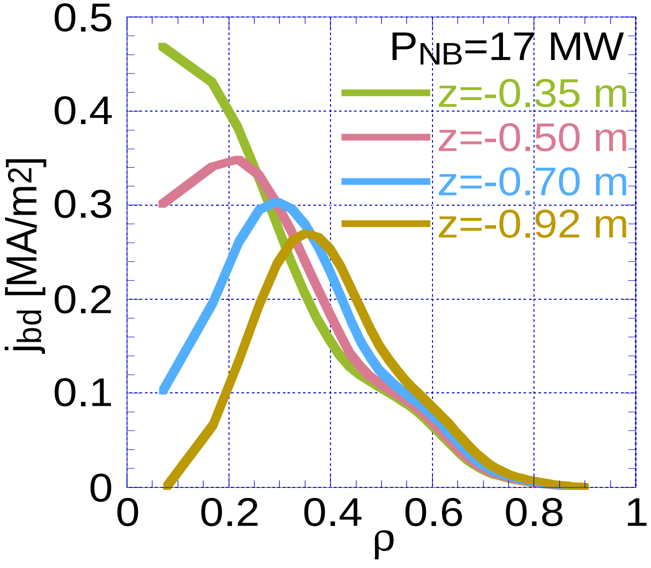
Overview of EC-launcher

Upper launcher :	poloidal steering	= - 60 ~ - 70°
	toroidal angle	= 24°
Equatorial launcher:	toroidal steering	= 20 - 45°
Equatorial port :	standardized port plug for IC/EC/LH	

Neutral Beam Injection for ITER

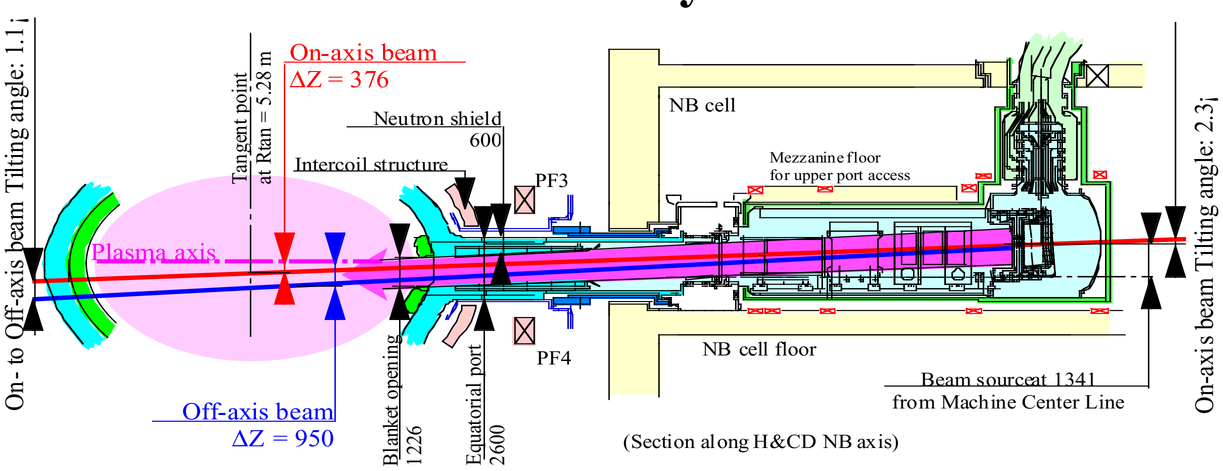
(1 MeV, 16.5 MW/Port)
Initial Installation 33 MW, Upgrade 50 MW

Beam Driven Current Profile



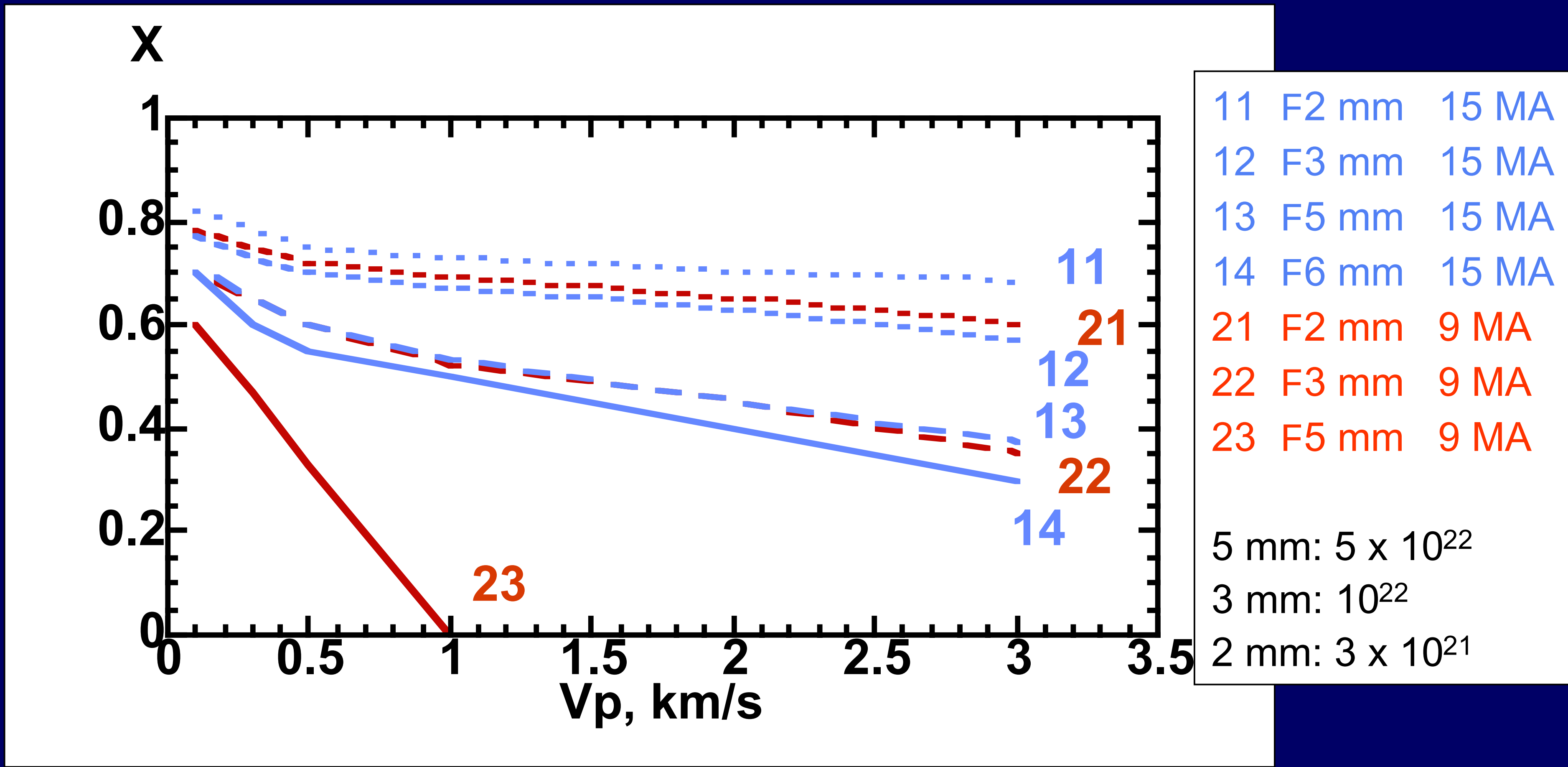
γ¯ 0.4x10^{20} A/Wm^2

NB Elevation Layout



Fuelling at r/a = 0.6 ~ 0.8 with HFS Pellets

HFS pellet speed ~ 300 m/s



Model: ablation by Kuteav, cloud size by Parks and mass relocation by Strauss

ITER Machine Capability

	Reference Performance	Flexibility
I_P (MA)	15 (flat top 400-500 s)	17 (flat top ~200 s)
Fusion power (MW)	500 (~2000s)	700 (~200s)
κ_x/δ_x	1.85/0.49	2.0/0.55(a=1.85m)

	Initial	Possible Upgrade	
NB (MW)	33	50	33
RF (MW)	40	80	100
ECCD for NT (MW)	(20)	(40)	
Saddle coils for RWM	20KA/10G/2Hz	~50KA	

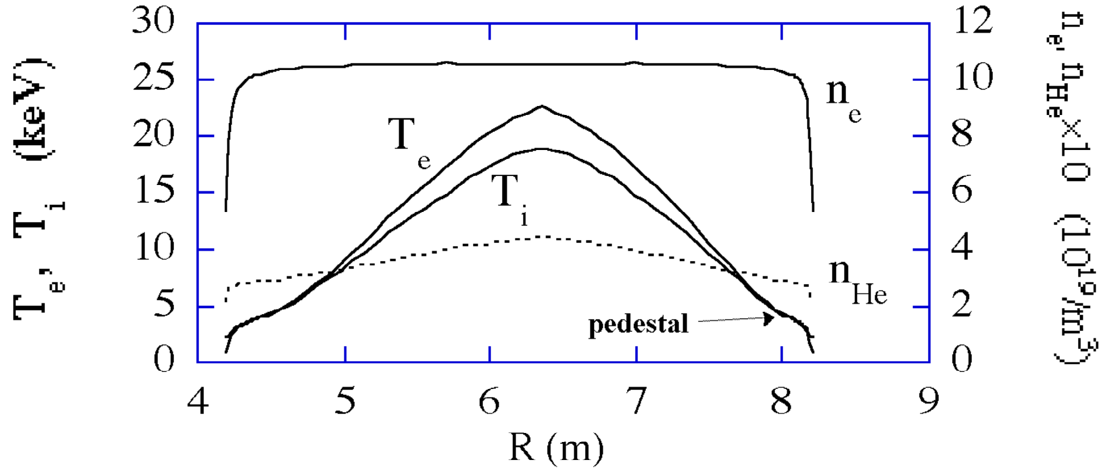
Plasma facing Components	Exchangeable, Attached to divertor/blanket body
Divertor/Blanket	Exchangeable
Large common ports	14 for blanket tests, RH, Diagnostics, H/CD

Standard Operation:ELMy H-mode

$$P_{LH} = 2.84 M^{-1} B_T^{0.82} \overline{n}_e^{0.58} R^{1.00} a^{0.81}$$

$$\tau_{E,th}^{IPB98(y,2)} = 0.144 I_P^{0.93} B_T^{0.15} P^{-0.69} n_e^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78}, \qquad \tau_E = H_H \tau_{E,th}^{IPB98(y,2)}$$

(s, MA, T, MW, $10^{20}m^{-3}$, AMU, m and $\kappa_a = S_X/\pi a^2$)



Conservative Assumption: 1) Flat Density Profile

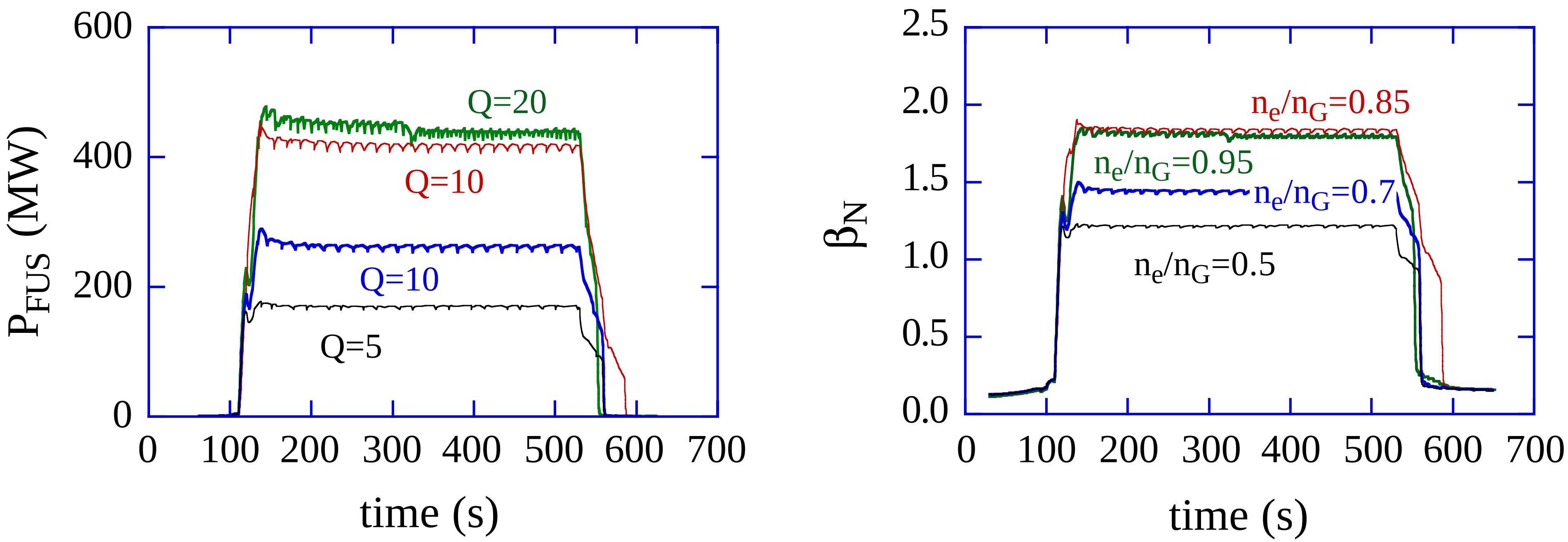
2) $P = P_\alpha + P_{oh} + P_{aux} - (P_{brem} + P_{cycl} + P_{line}/3)$

Radiation Loss ~ 30 %

3 j $\chi_i/\chi_e = 2$

Profiles: little flexibility (sawteeth oscillation, pedestal with ELMs and constant E_t)

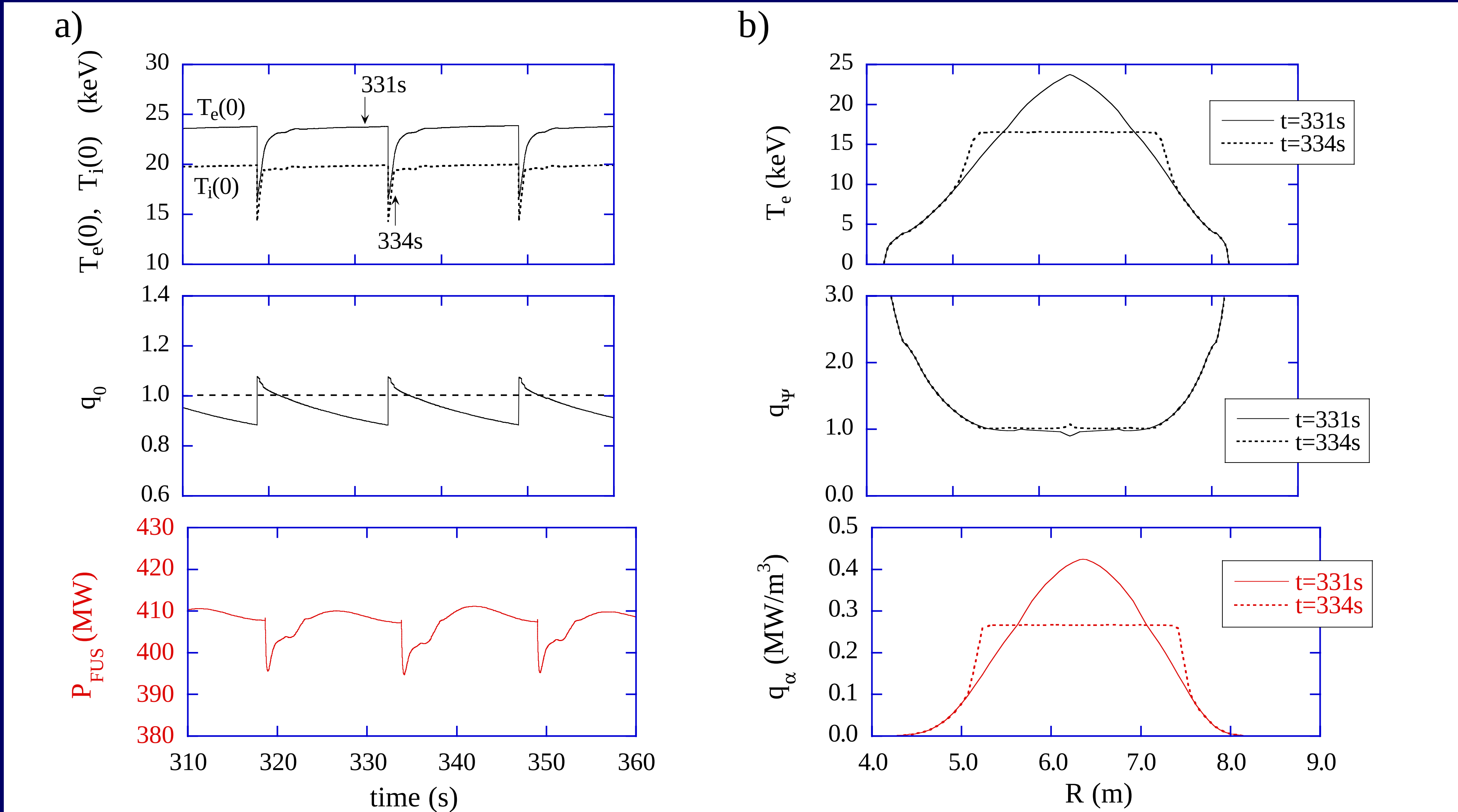
Fusion Power and Q increase as increasing Density



I_P = 15 MA, H_H = 1.0, τ_{He}^*/τ_E = 5, Divertor heat flux 10 MW/m^2

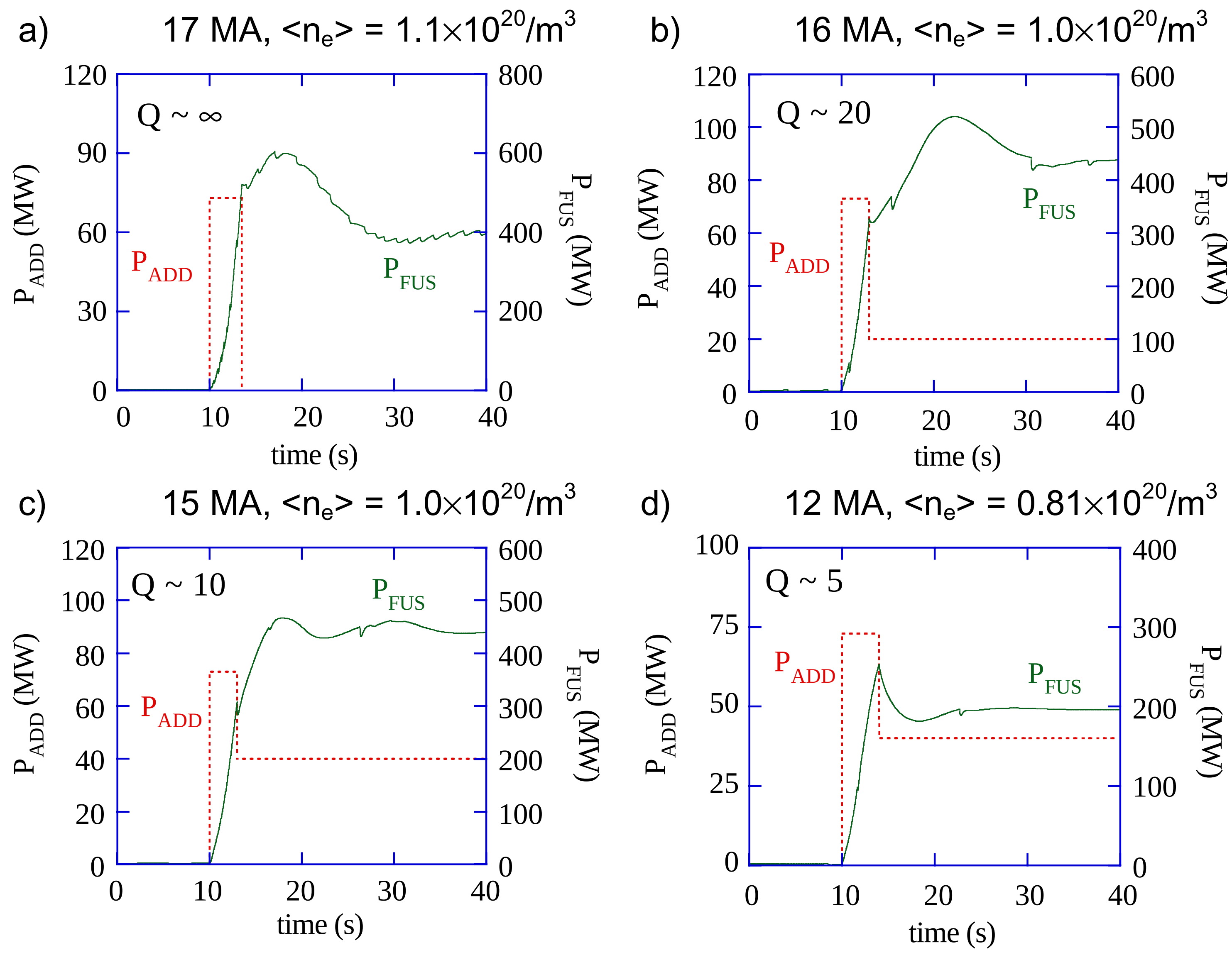
n_G (10^{20}/m^3) = I_P (MA) / πa^2, β_N = β (%) / [I_P/aB_T]

Small Fusion Power Fluctuations due to Sawteeth

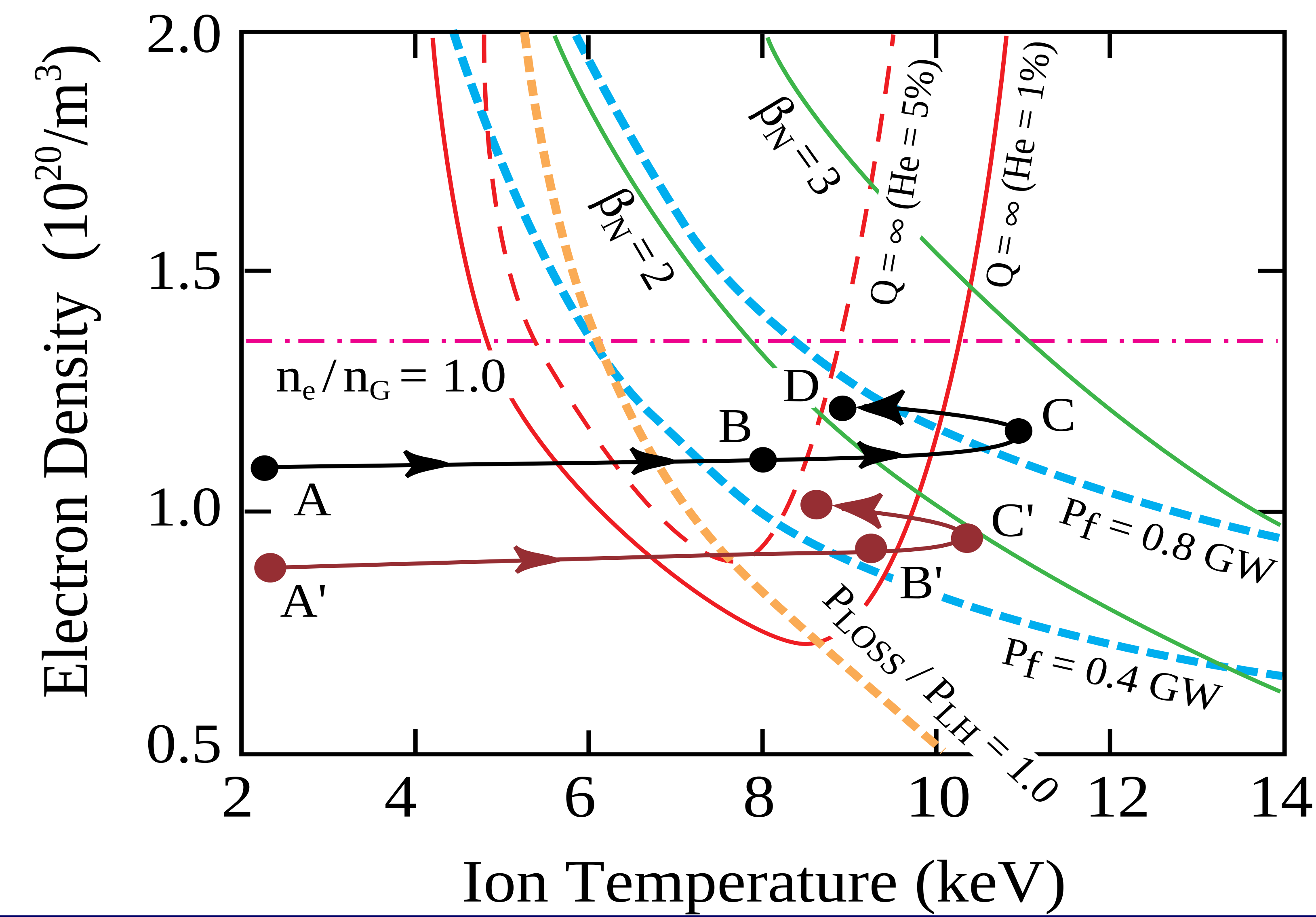


Operation points: thermally stable

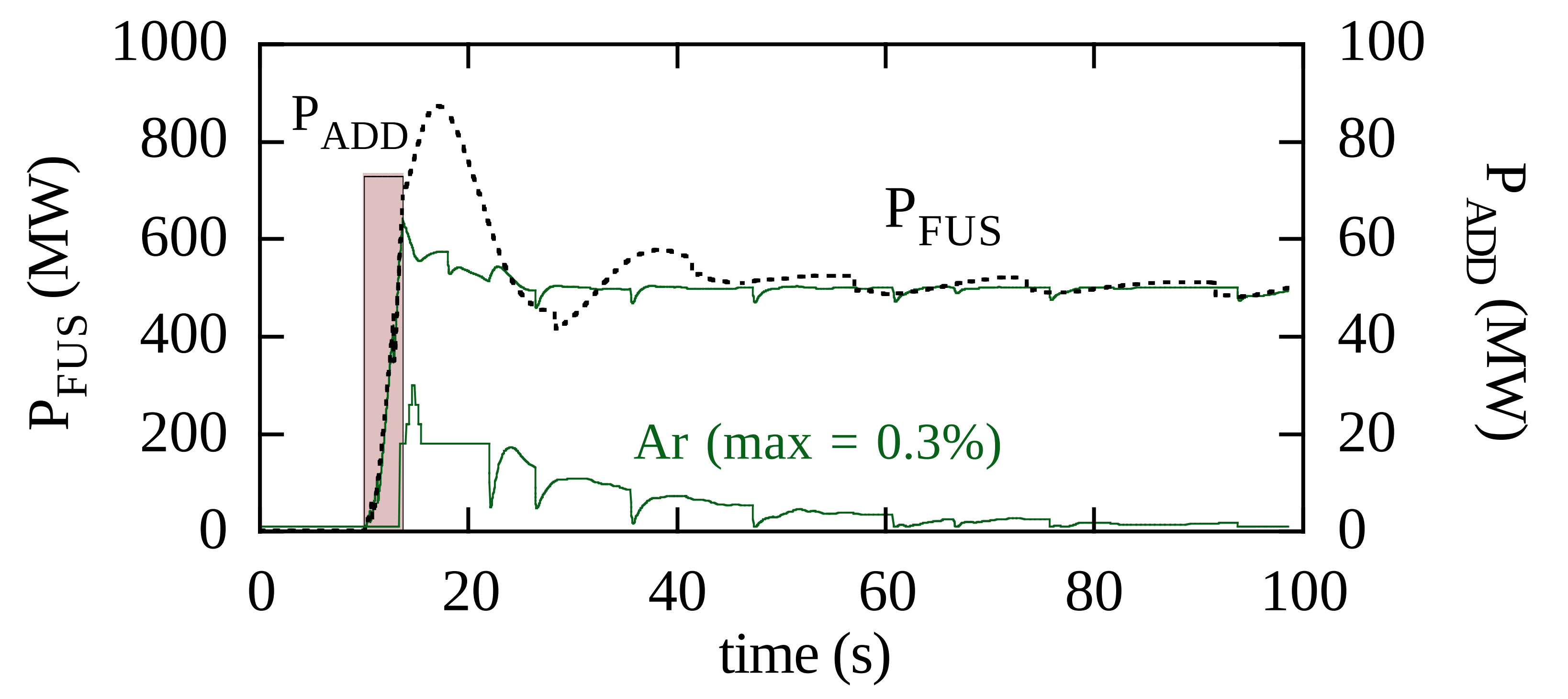
Fusion Power Excursion with I ≥ 15 MA



Fusion Power Excursion at 17 MA

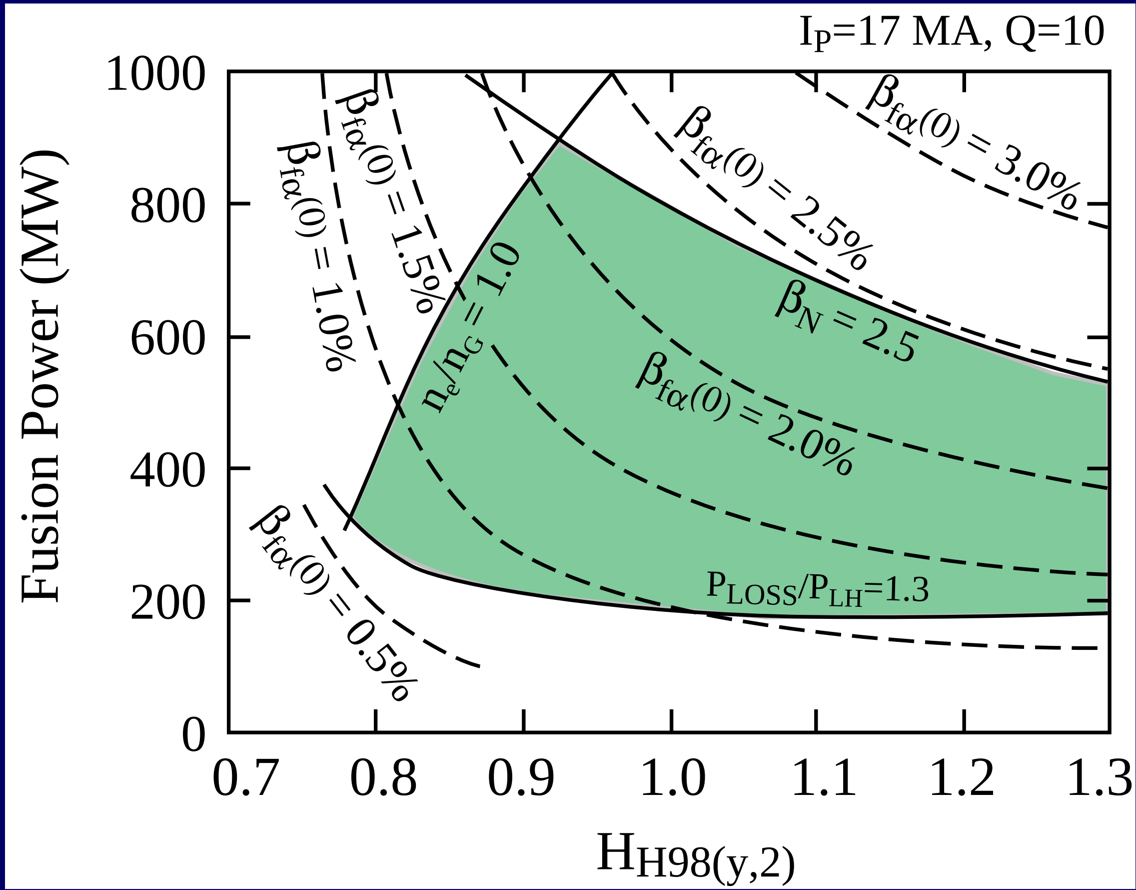


Control of Power Excursion by Impurity Injection



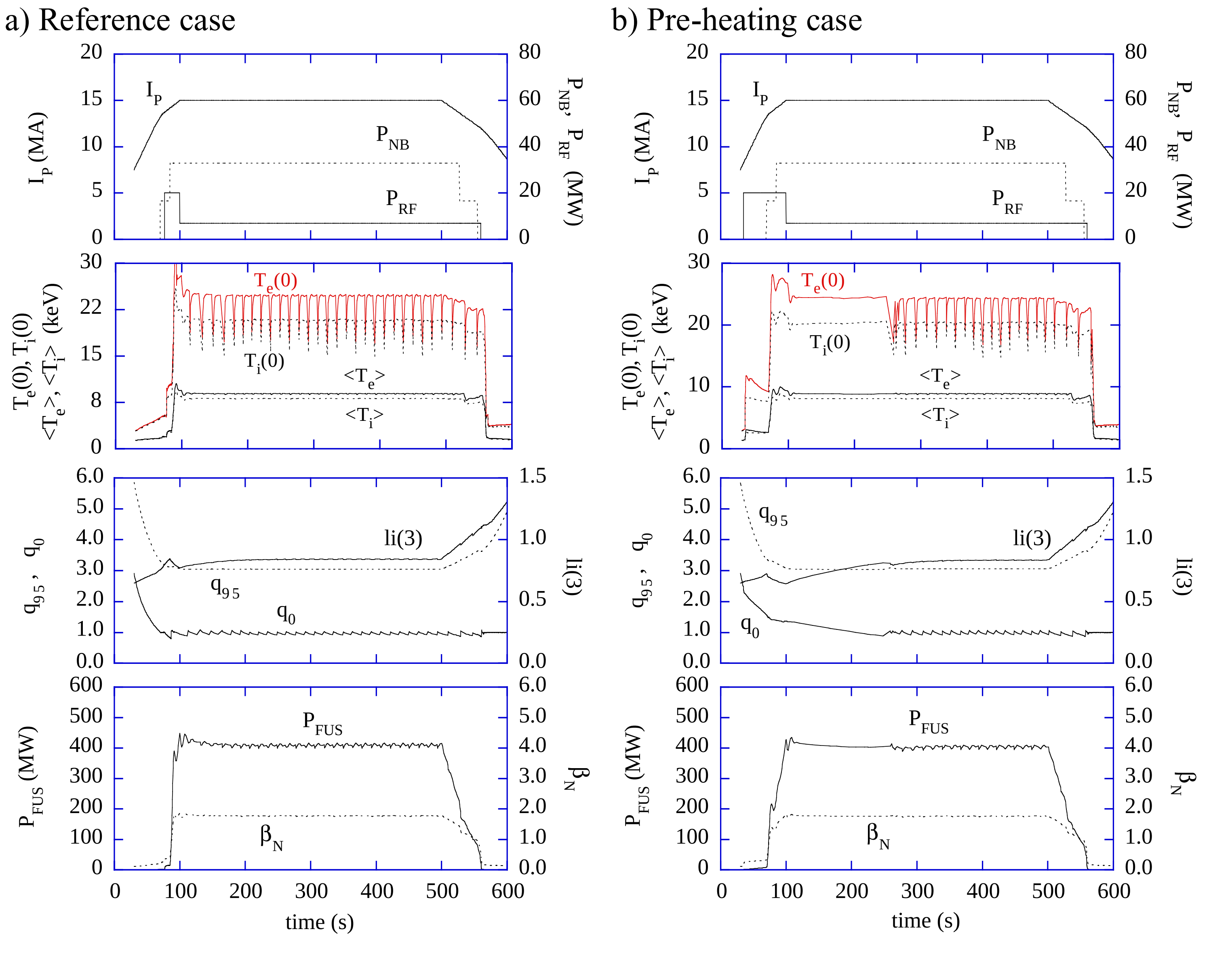
I_P = 17 MA, τ_{He}^{*}/τ_E = 3, $H_H(y,2)$ = 1.0 and 73 MW of heating power (P_{ADD}) is added from 10s to 13.7s: solid line - with argon (Ar) impurity seeding, dotted line - without impurity seeding

Fast Alpha Particle Beta in ITER (17 MA)

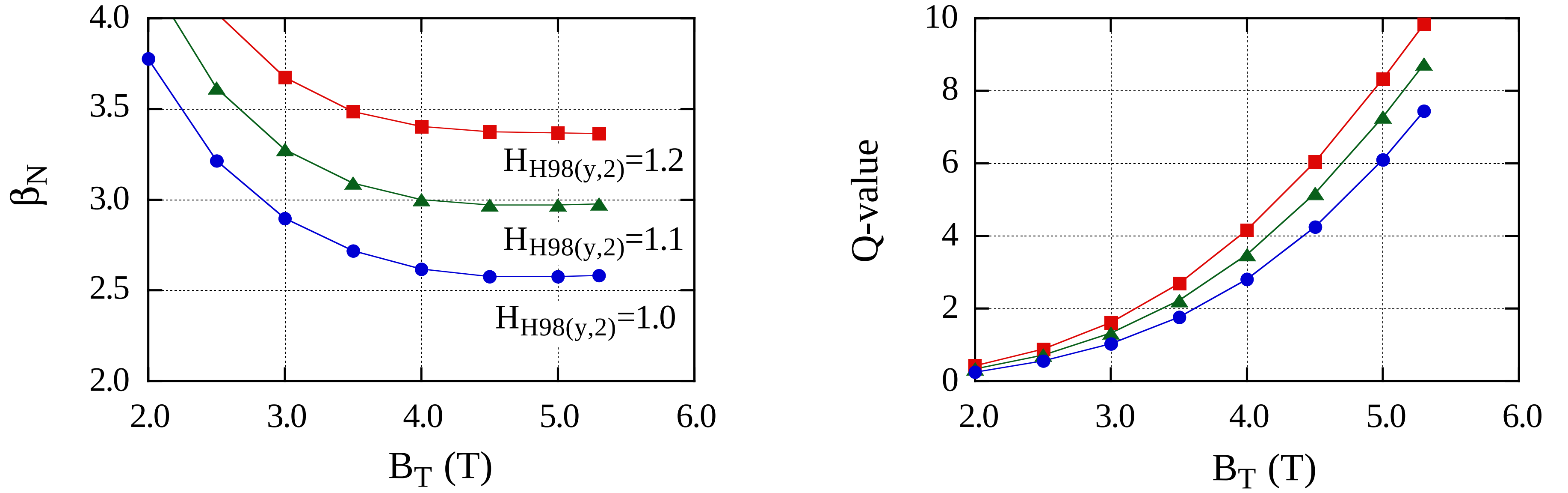


- High fast alpha particle beta: only with high confinement and heating power.
- Normally fast alpha particle beta on the axis: ~ 1 %

Control of Onset of the First Sawteeth



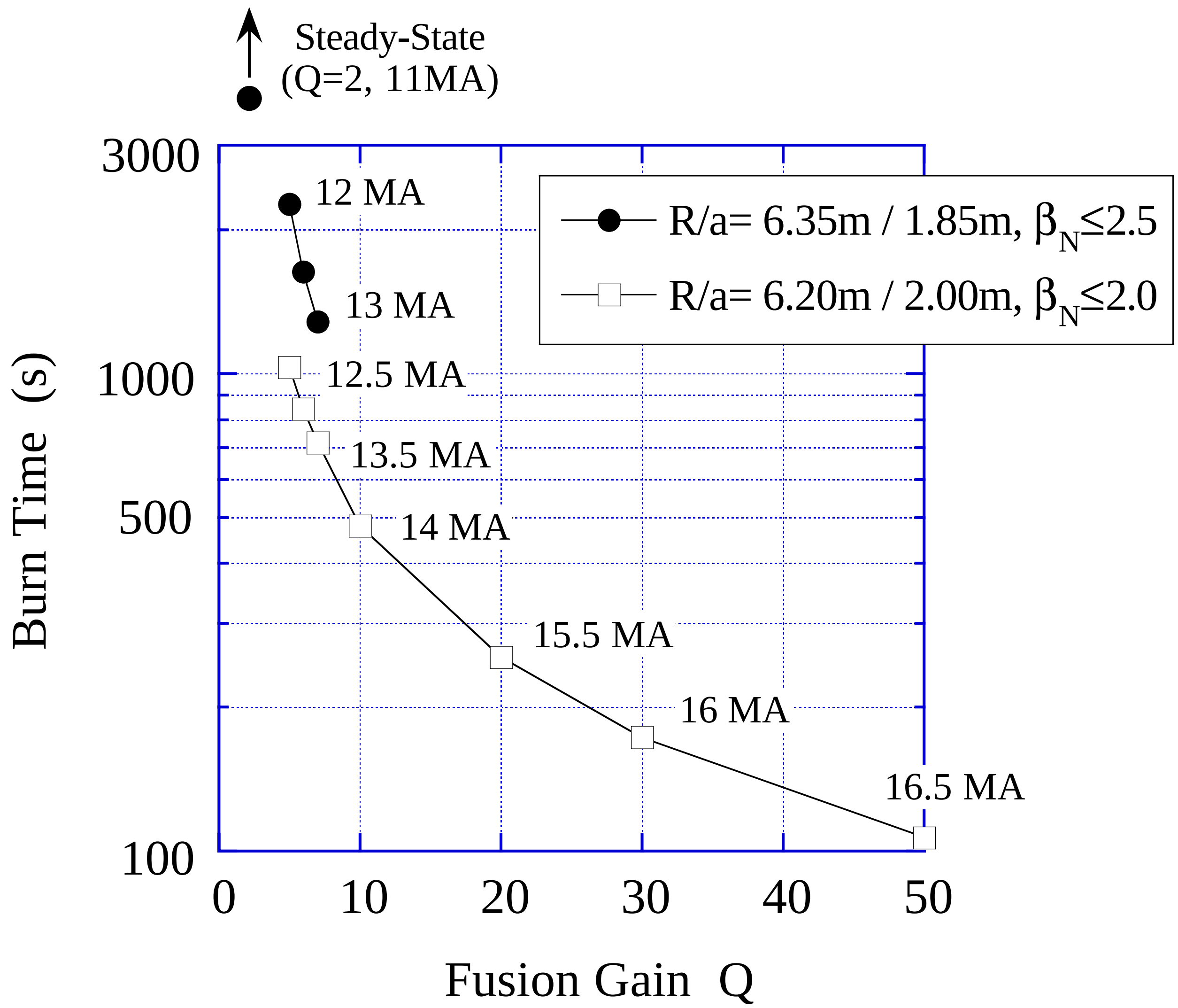
Possibility of High Beta and High Power in Inductive Operation



q_{95} = 3.0, $\langle n_e \rangle / n_G$ = 1.0, P_{ADD} = 100 MW

Study of controllability especially of heat exhaust will give fundamental data for pulse reactor development.

Pulse Length v.s. Q



H_H=1 and n_e/n_G † 0.85, P_{FUS} = 400-700 MW

0.3 Mwa/m^2 : ~ 14,000 Shots, ~1/3 Machine Life Time

Conditions to achieve Q = 5-6 Steady State Operation with Flat Density Profile

- $H = 1.5 \sim 1.6$, $\beta_N = 2.7\text{-}2.9$, $P_{CD} = 60\text{-}70$ MW, $I_P = 9\text{-}9.5$ MA, Impurity seeding to reduce loss power.

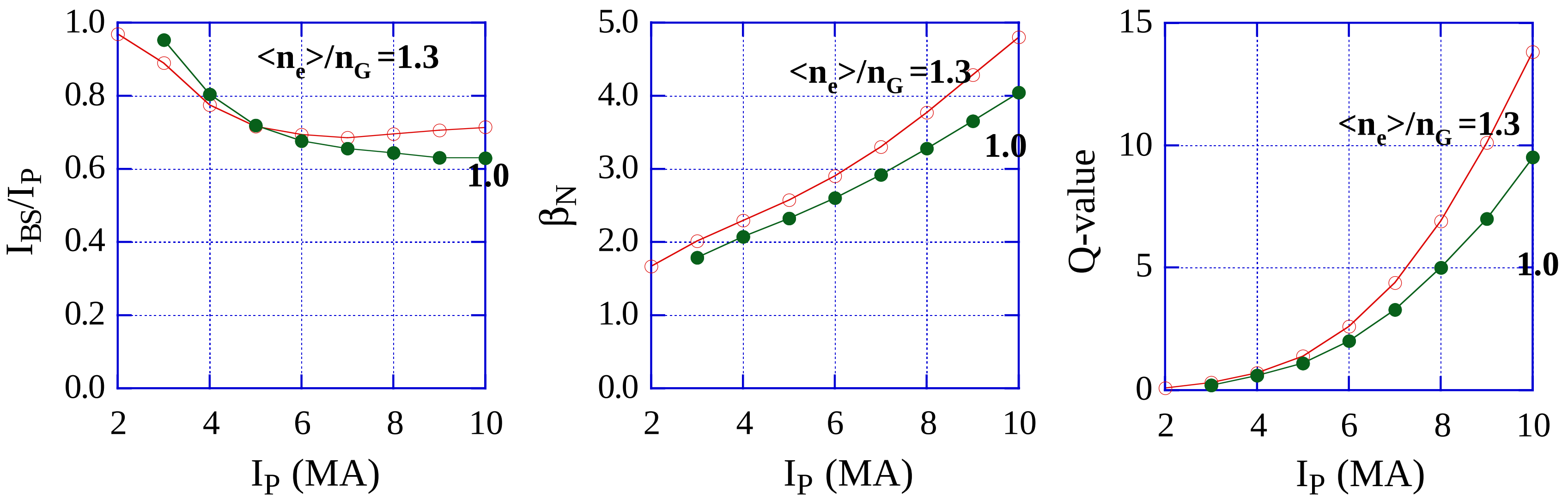
- In some cases, $\beta_N \sim 4\ l_i$ and RWMs would be stable.

- This would be achieved with a large radius (~ 0.7 a) of internal transport barrier in a shallow q profile discharge.

- This would be a possible mode to achieve Q = 5-6 in ITER and to study interactions among self heating, current profile, transport, pressure profile, etc.

Possibility of High Bootstrap Current and High Beta

(I_P † 9 MA), $n_{axis}/\langle n_e\rangle=1.3$, P_{ADD} = 100 MW, H_H = 1.5, R = 6.35 m, a = 1.85 m



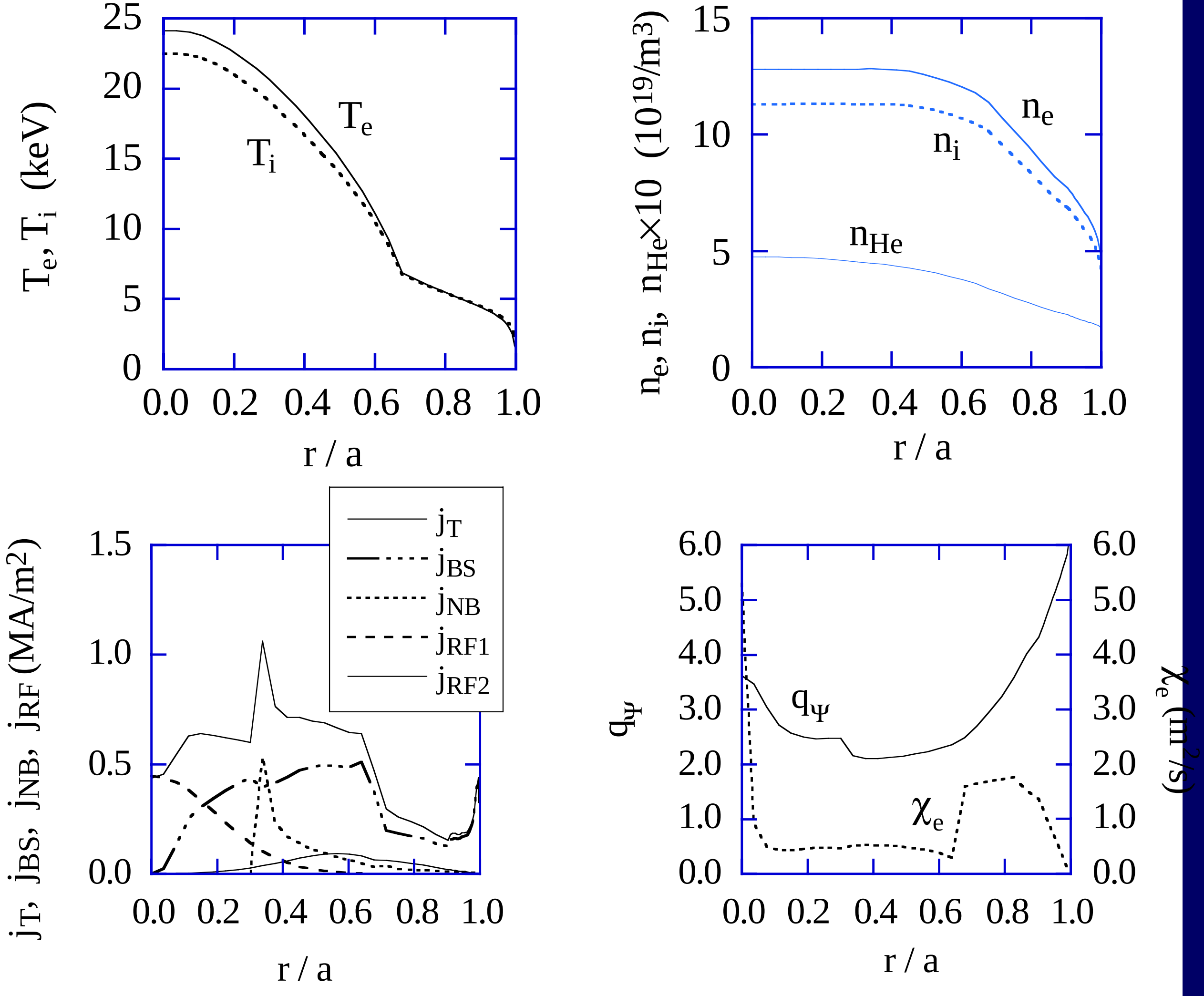
Issues

Density profile:	**pinch or deep fuelling**
Power exhaust:	**total power of ~250 MW**
Stabilization of RWMs:	**$\beta_N > 4\ l_i$**
Self organization of profiles:	**pressure, current, fusion power .**

- This challenging area will be necessary to explore for reactor development but with a limited pulse length.

- In parallel with ITER, experimental and theoretical work is in dispensable.

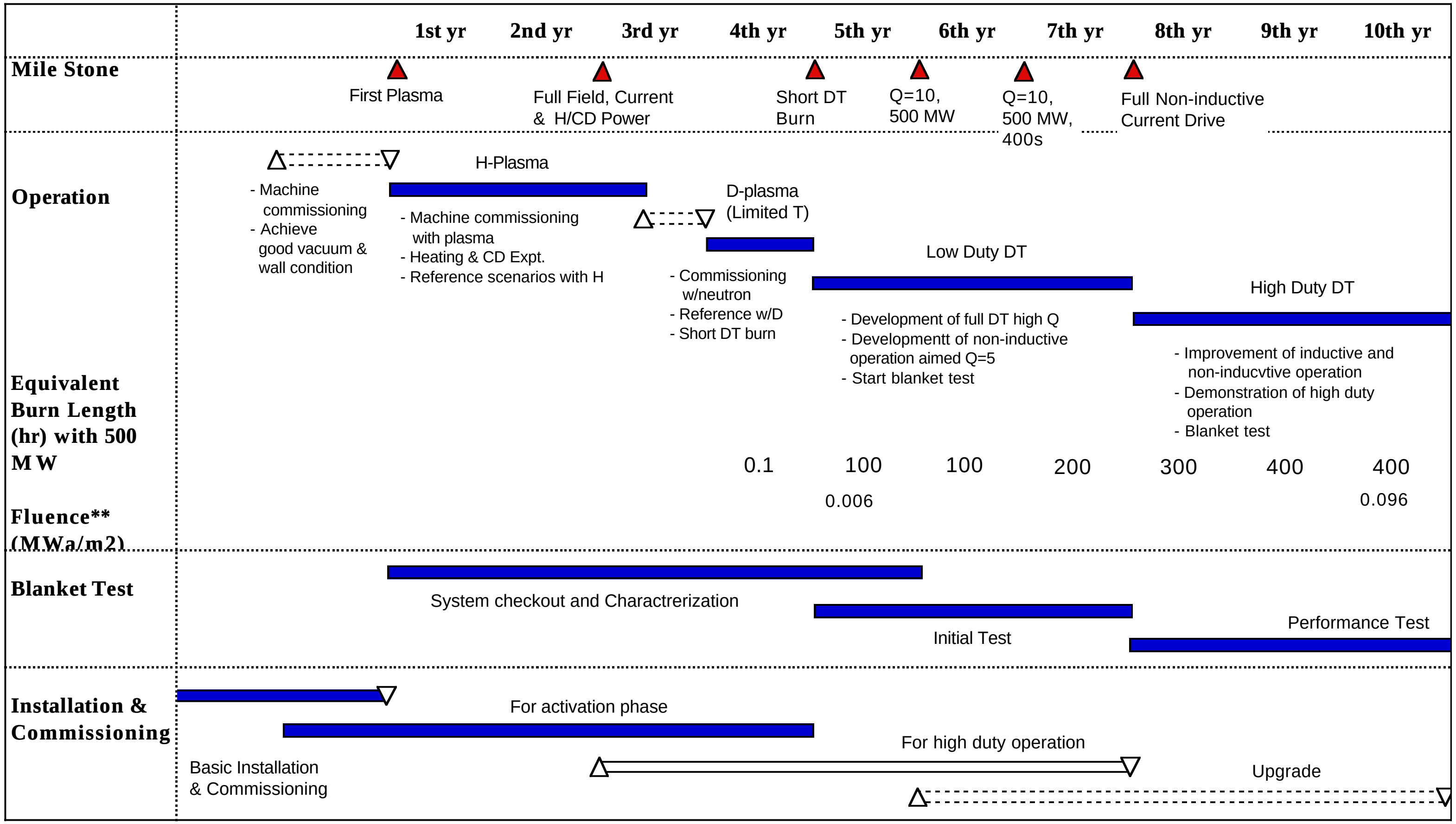
Steady State Operation with Peaked Density Profile



P_{FUS} = 778 MW, Q = 7.8, β_N = 4.0, $<n_e>/n_G$ = 1.3,

I_P = 8.5 MA, $H_{H98(y,\,2)}$ = 1.52, P_{CD} = 100 MW, I_{BS} = 6 MA,

I_{CD} = 2.5 MA, $\gamma = I_{CD} <n_e> R/P_{CD} = 0.2 \times 10^{20}$, $V_P = 0.5\ Dq'/q$



*Average Fluence at First Wall (Neutron wall load is 0.56 MW/m2 in average and 0.77MW/m2 at outboard midplane.)

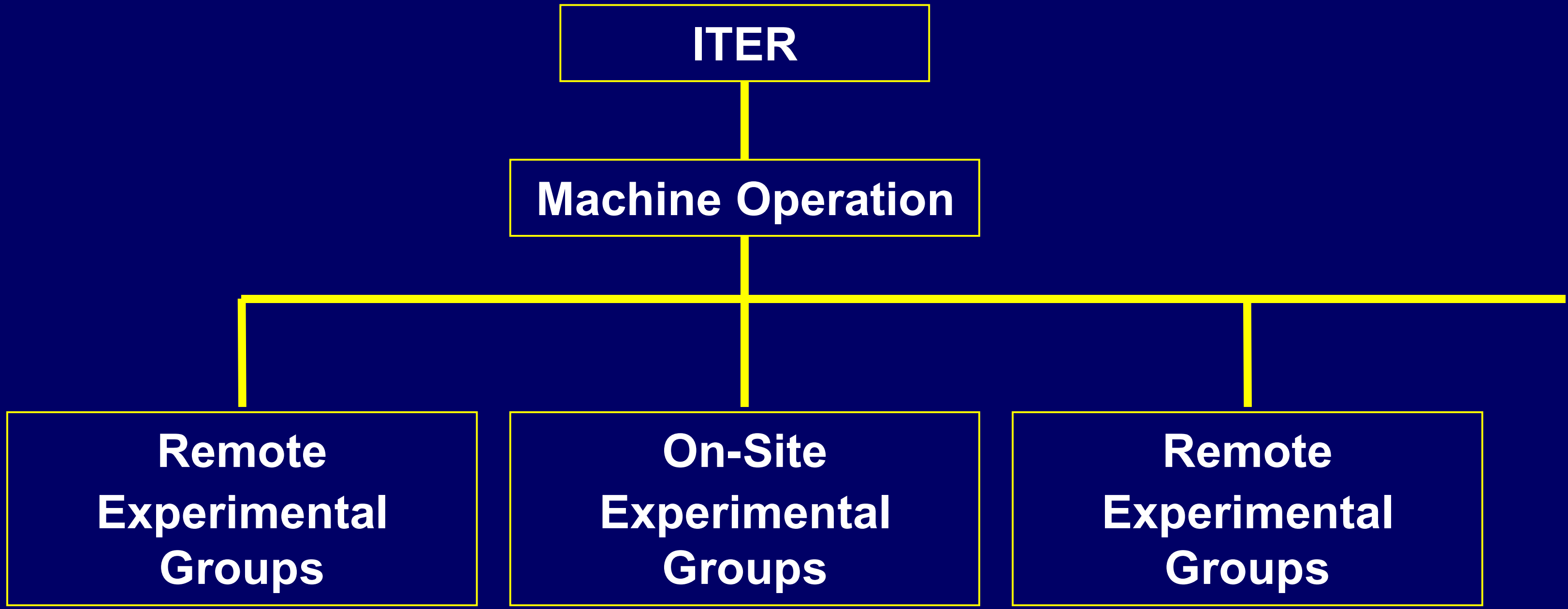
Net consumption of tritium

The first ten years	~ 5kg
Average 0.3/Blanket test area 0.4 MWa/m^2	~ 15 kg (Minimum requirement)
Average 0.5/ Blanket test area 0.7 MWa/m^2	~ 25 kg (Design value)

~30kg of tritium could be supplied with external sources

Worldwide Exploitation

Efficient use of ITER, Involvement of worldwide fusion community, Close interaction with domestic programmes and Promotion of Scientific Competition



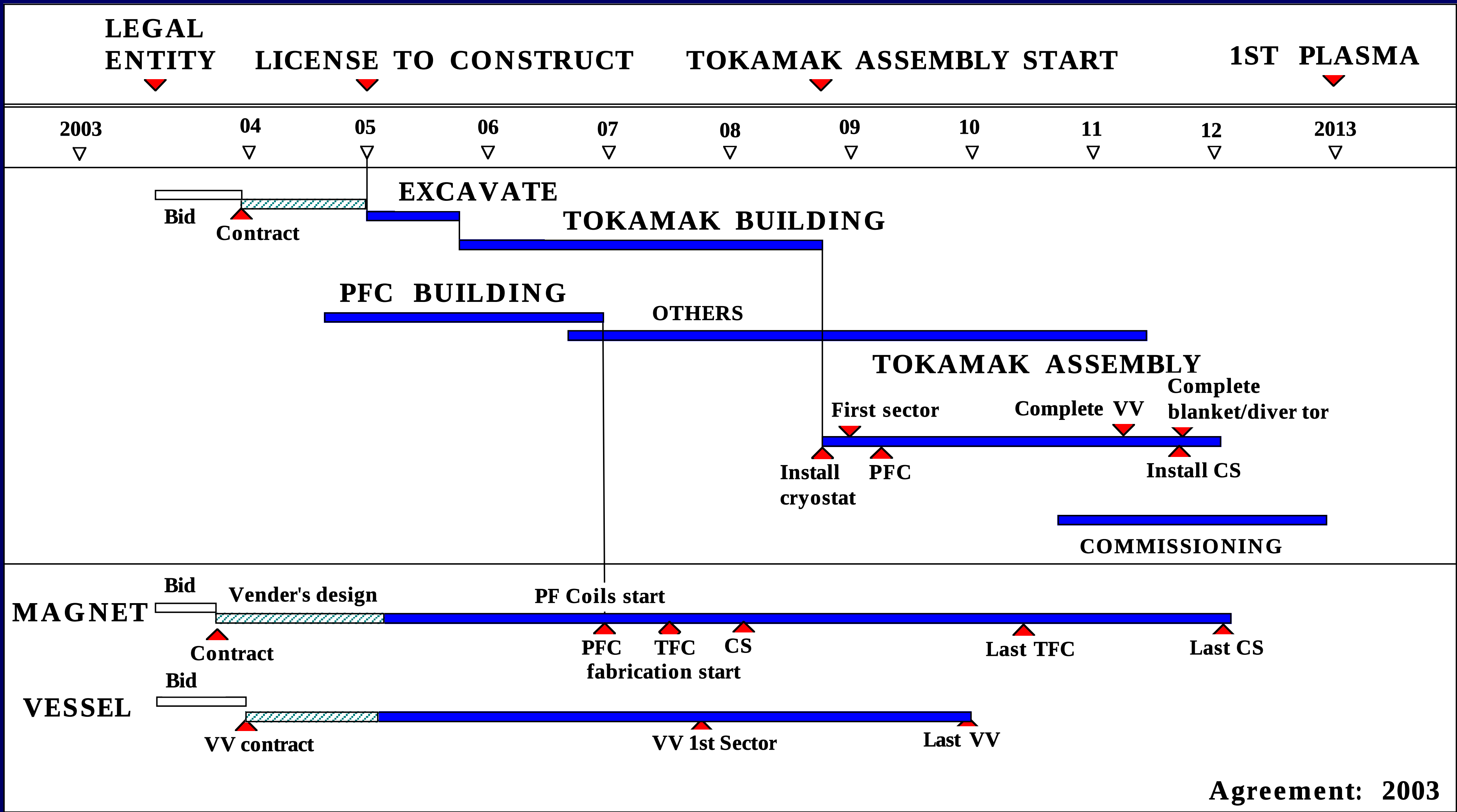
Operation mode:

- 3 shift/day on site: Most people during day(1st/2nd shifts) for experimentation. Less people during night shift for machine monitoring and support of remote experiments.
- 1 or 2 shift(s)/day on remote experimental sites: Experimentation during day

Staff:

Encourage mobility, Minimize directly employed staff and Ensure scientific participation by short term personnel or groups from universities or institutes.

ITER



June 7, 2001: The first site offer with Canadian Government endorsement.

Conclusions

The flexibility of ITER will allow research in a large operation space.

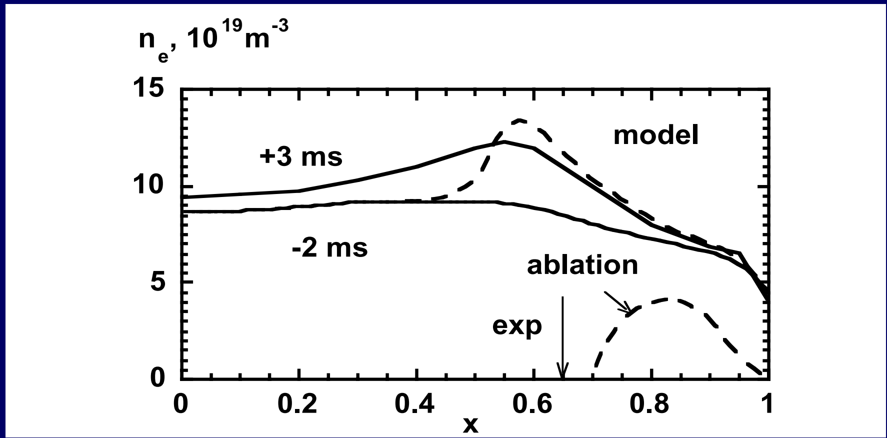
P_{fusion}, Q, n, β, pulse length, I_P -----

Confirm predictable operation ⇒ Explore frontier (Physics, Reactor)

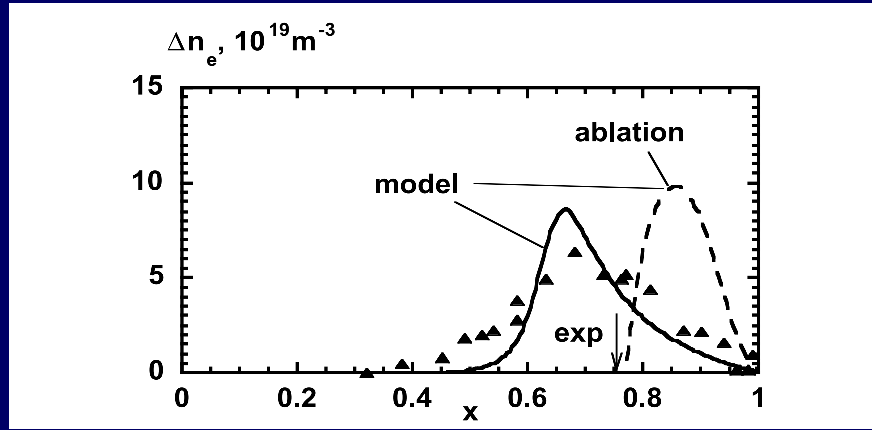
- Predictable operations and extended operations with inductive current drive
  150 700MW , n/n_G=0.5 1 , β_N =1.2 2.5, Q = 5 10 20 ∞
  ~ 100 s burn is necessary to study plasma behavior.
- Hybrid operations
  > 1000 s / 500 MW/Q=5 with reasonable parameters for blanket test (0.77 MW/m^2)
  If necessary, q_{95} > 3.5 scenarios is available.
- Research of fully non-inductive driven operations aiming at Q=5 and a higher value
  (higher β/higher confinement, methods included in ITER)
  ~ 2000 s is necessary to achieve steady state of AT mode from conventional one.
  By optimizing current ramp-up, steady state of AT can be achieved within 200 s.

The experimental concept will increase efficiency, involve the worldwide fusion community and promote scientific competition.

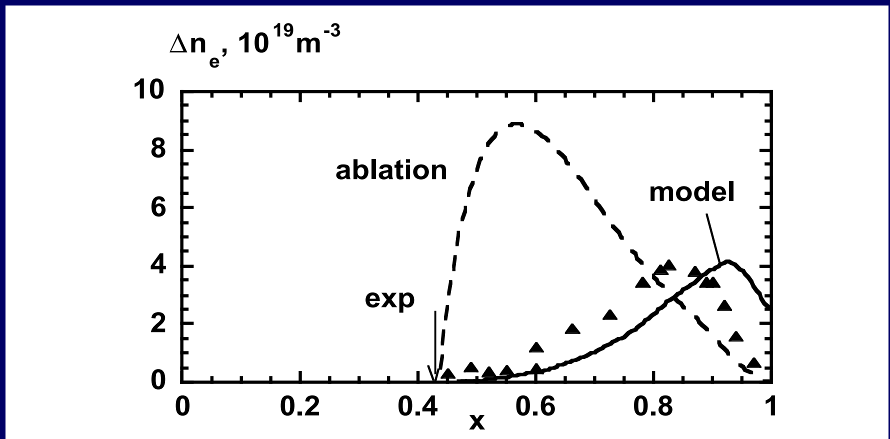
High Field Side Pellet Injection



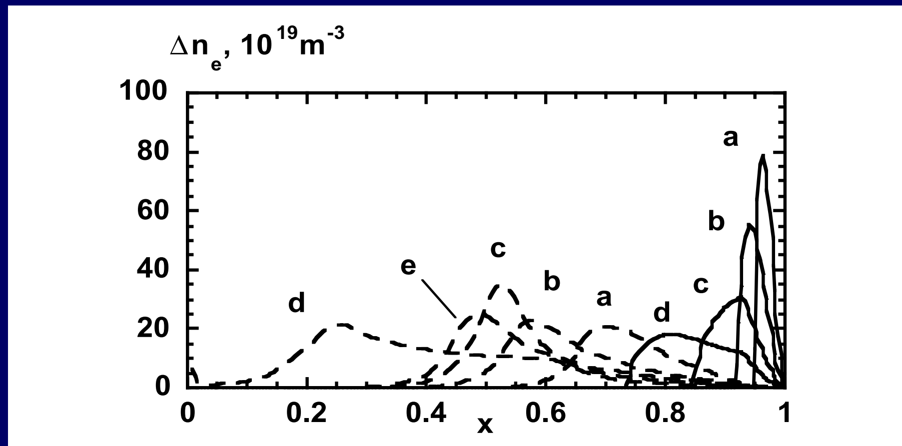
AUG/H



D-III-D/H



D-III-D/L



ITER/H

a : 100m/s , b:300m/s,c:1000m/s, d: 3000m/s

D = h = 1 cm

By A. Polevoi (Kuteav/Parks/Strauss, ablation/cloud size/mass relocation)