Fusion Reactor Technology I
(459.760, 3 Credits)

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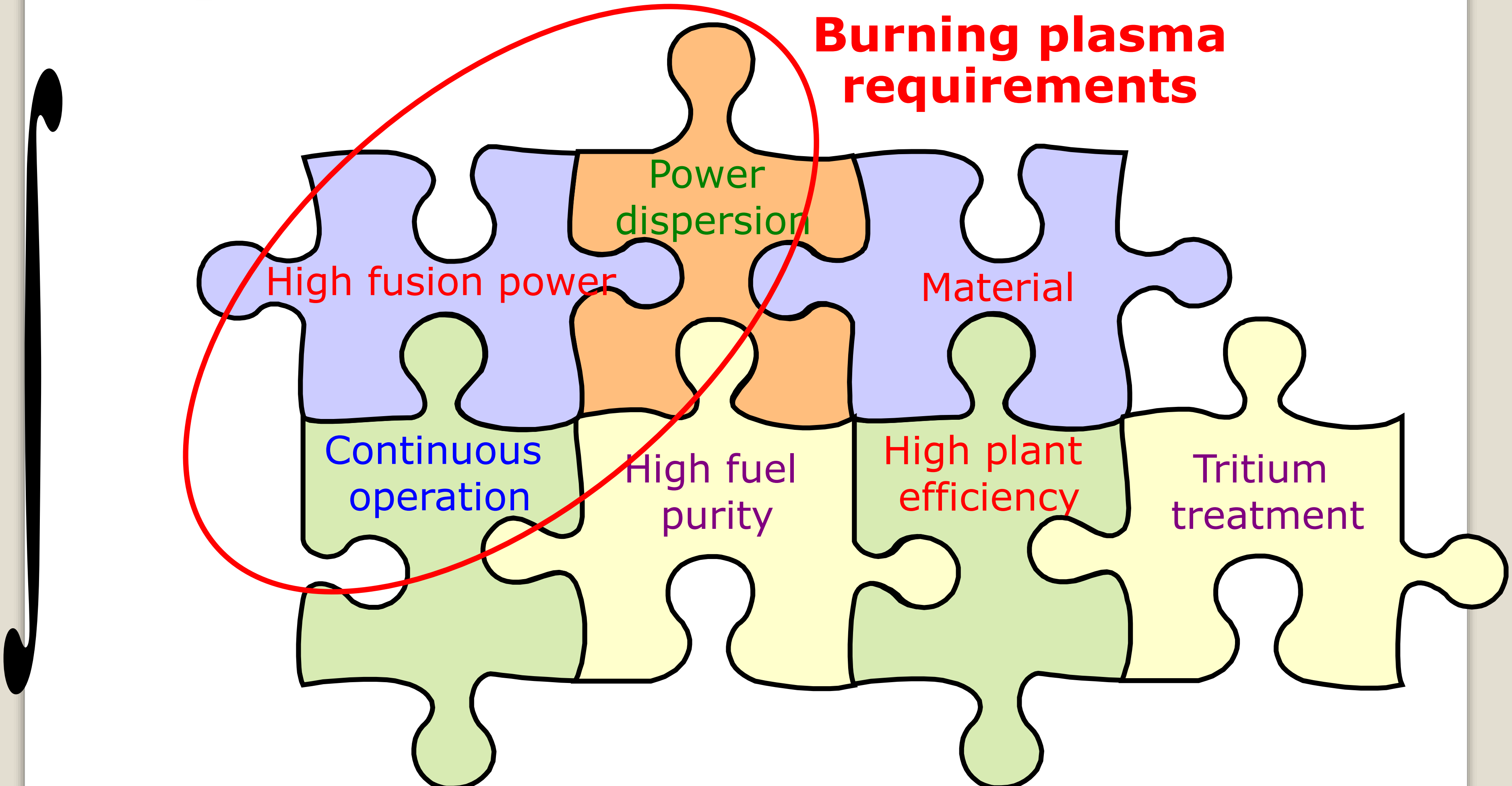
(32-206, Tel. 880-7204)

Contents

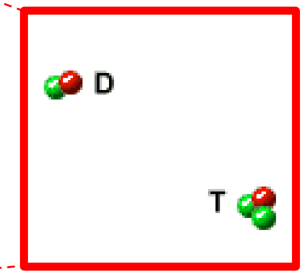
Requirements for FPP



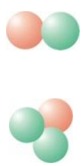
3

Fusion Reactor Energetics

What is required to light a fire in a stove?



- Fuel: D, T
- Amount/density: n
- Heat insulation: τ
- Ignition temperature: T



Deuterium

Tritium

$\geq ?$

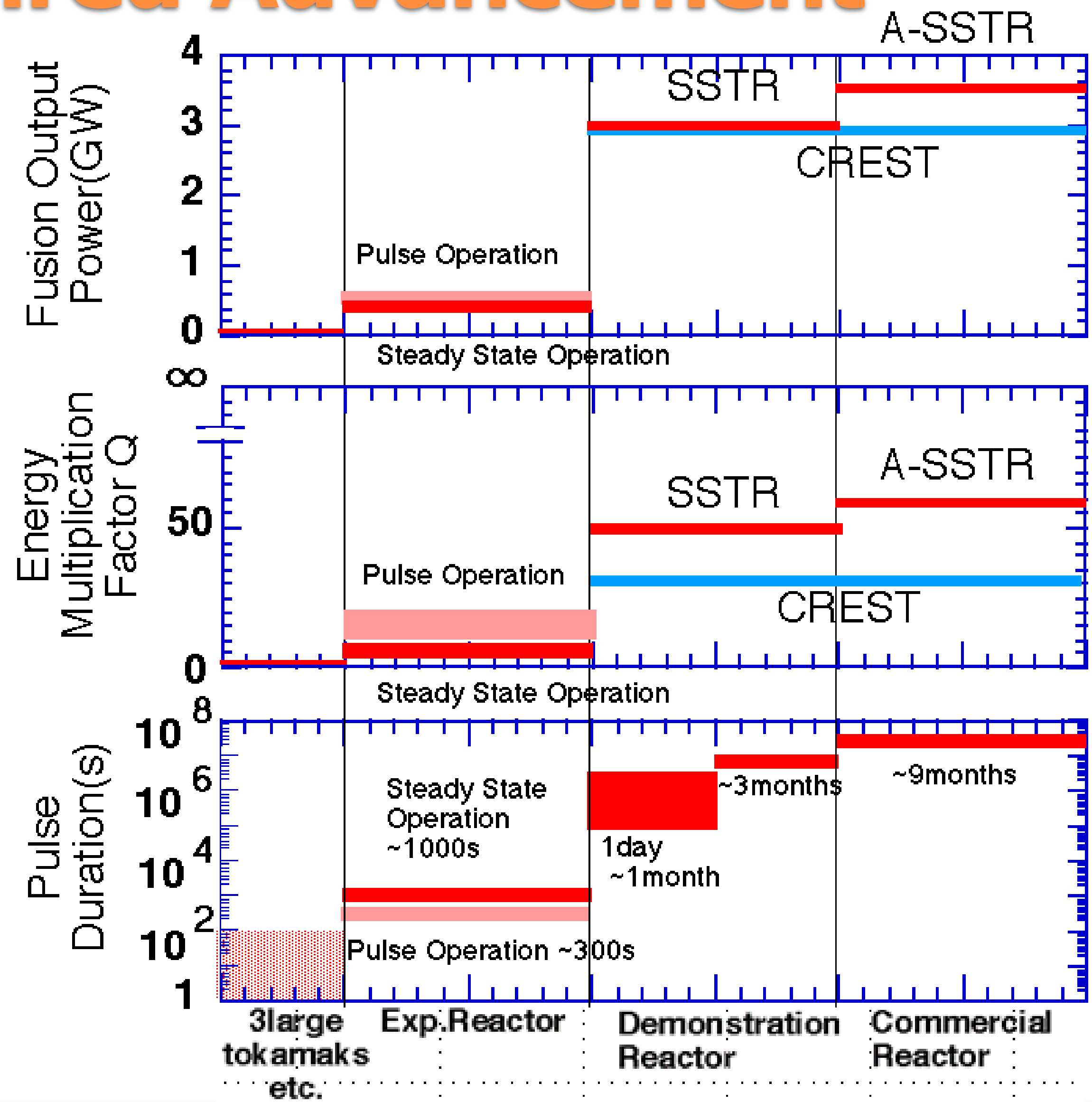
quired

Lawson Criterion

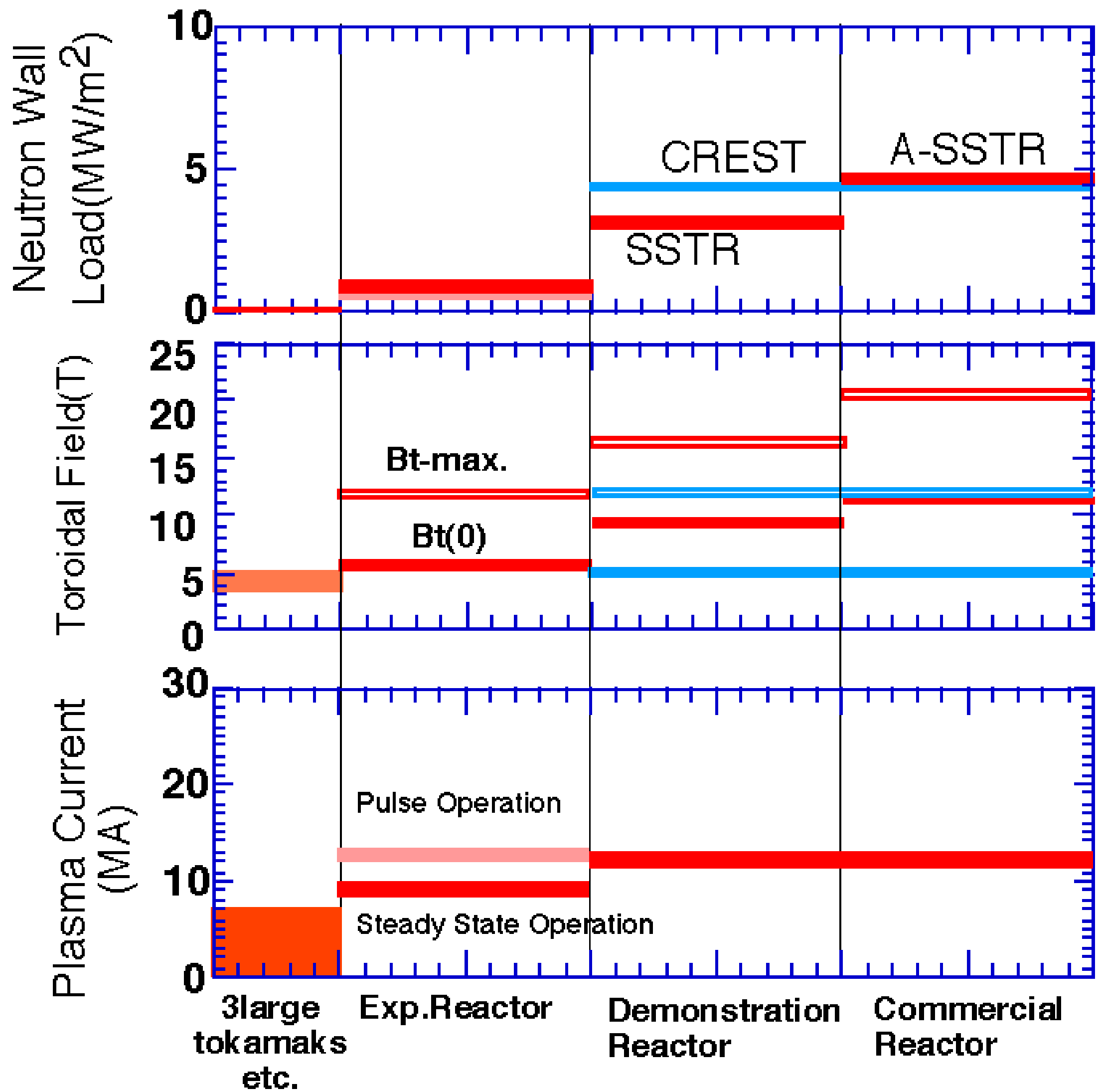
Required Advancement

1. Fusion output power
2. Energy multiplication factor
3. Pulse duration
4. Neutron wall load
5. Toroidal magnetic field
6. Plasma current
7. Normalized beta
8. Operation density
9. Heat exhaust and radiative cooling
10. Helium exhaust
11. Self-heating fraction and heating control
12. Current drive efficiency
13. Simultaneous attainment

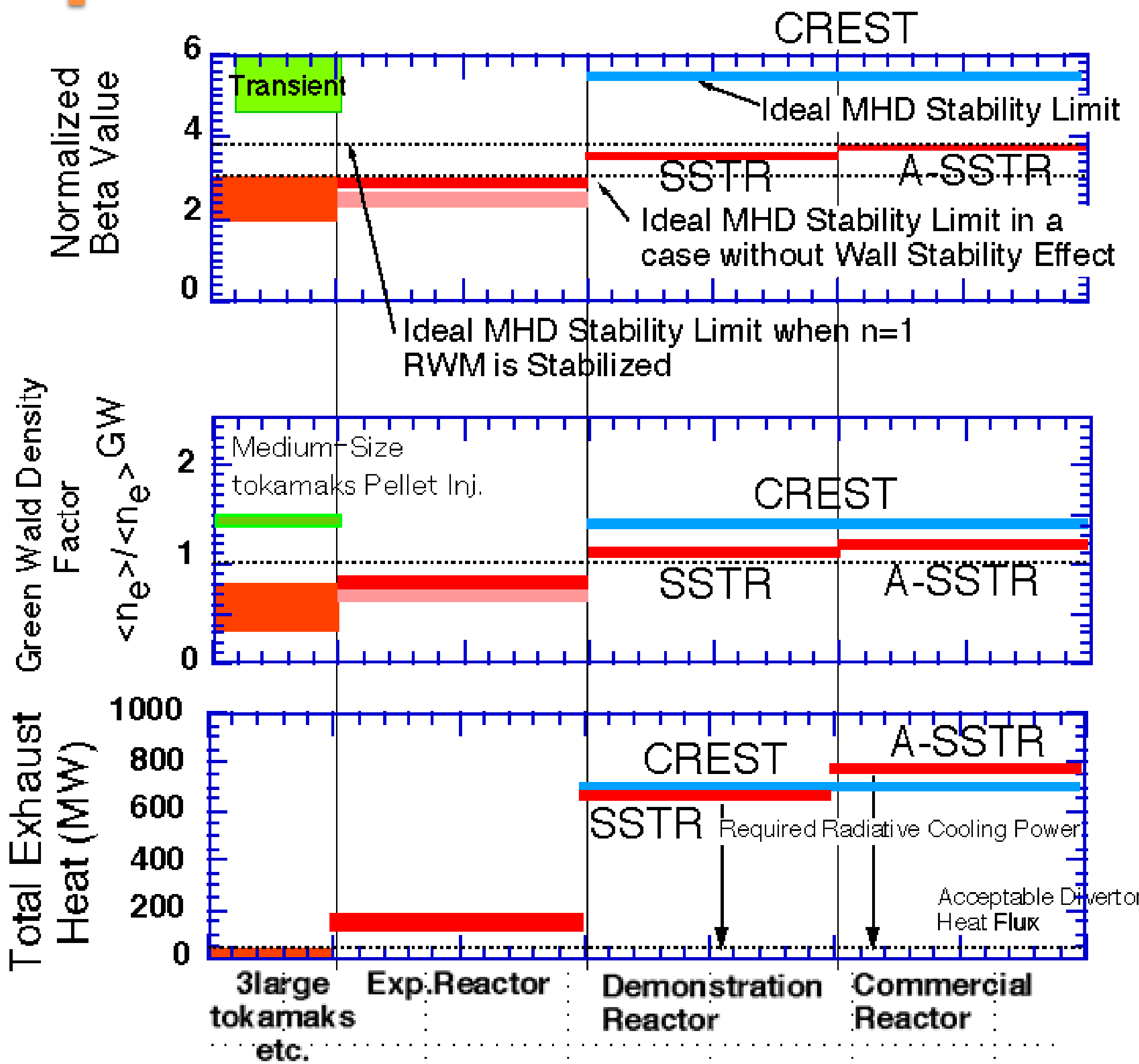
Required Advancement

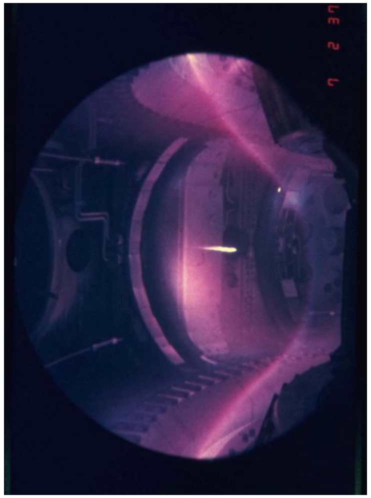


Required Advancement



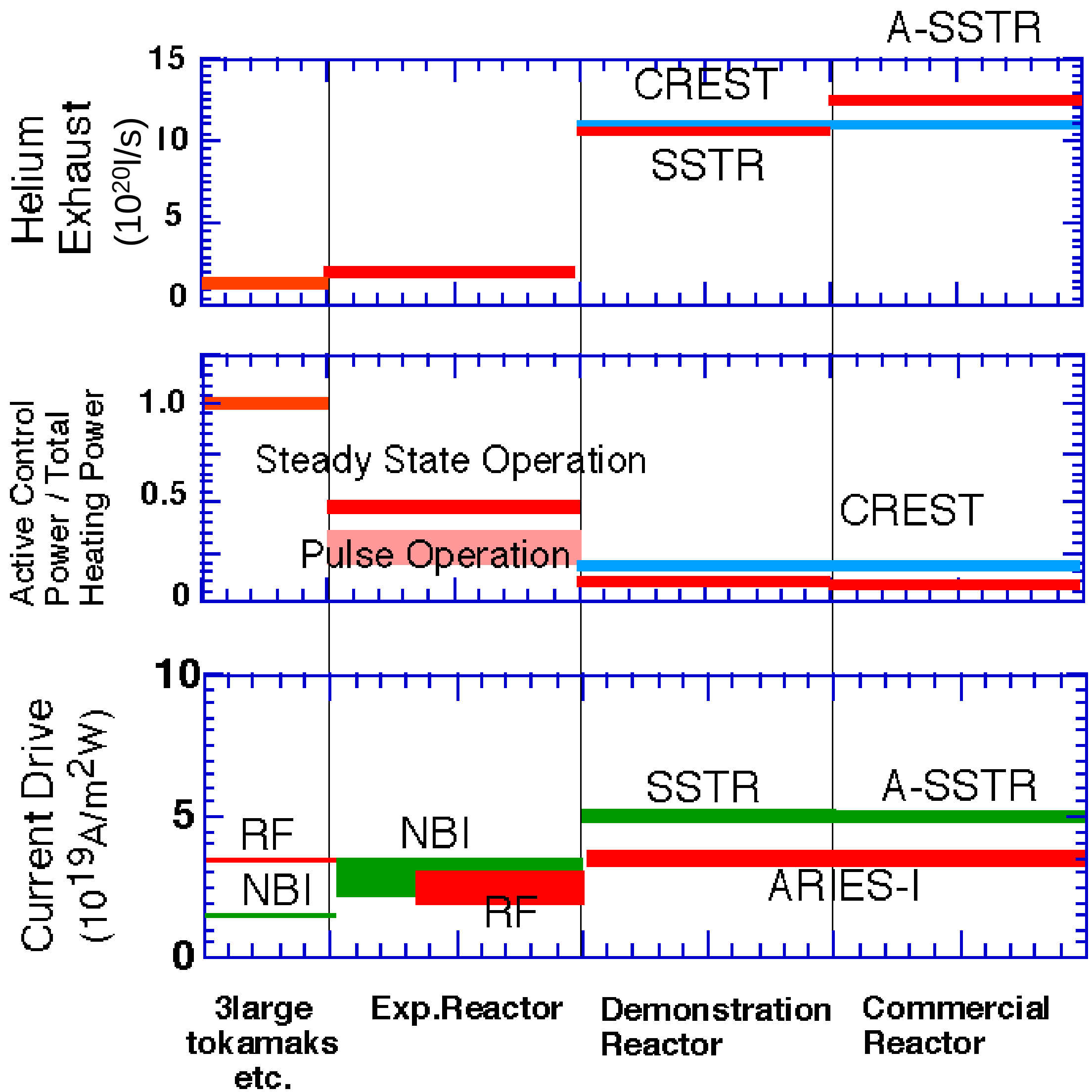
Required Advancement



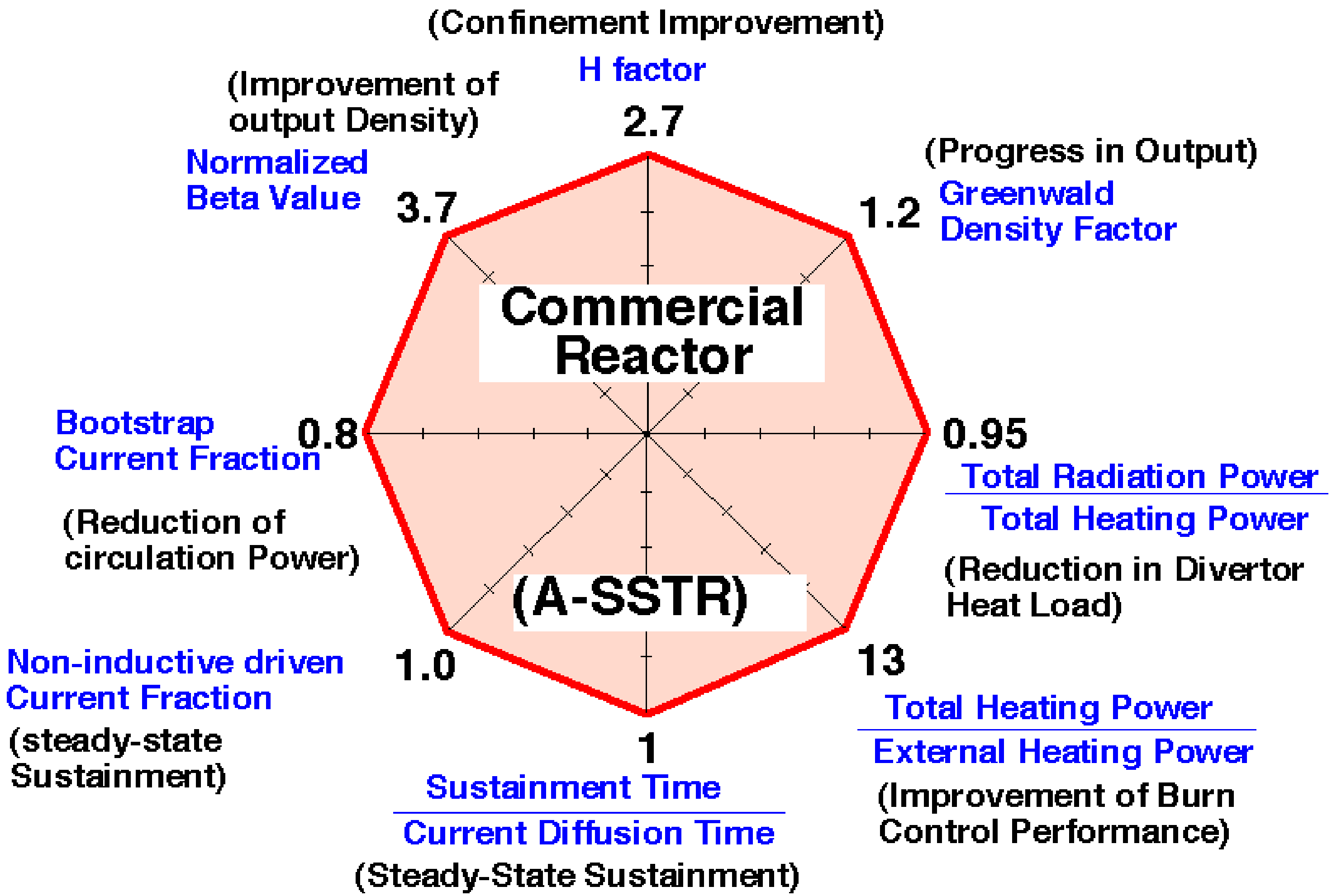


- Pellet injection in ASDEX Upgrade

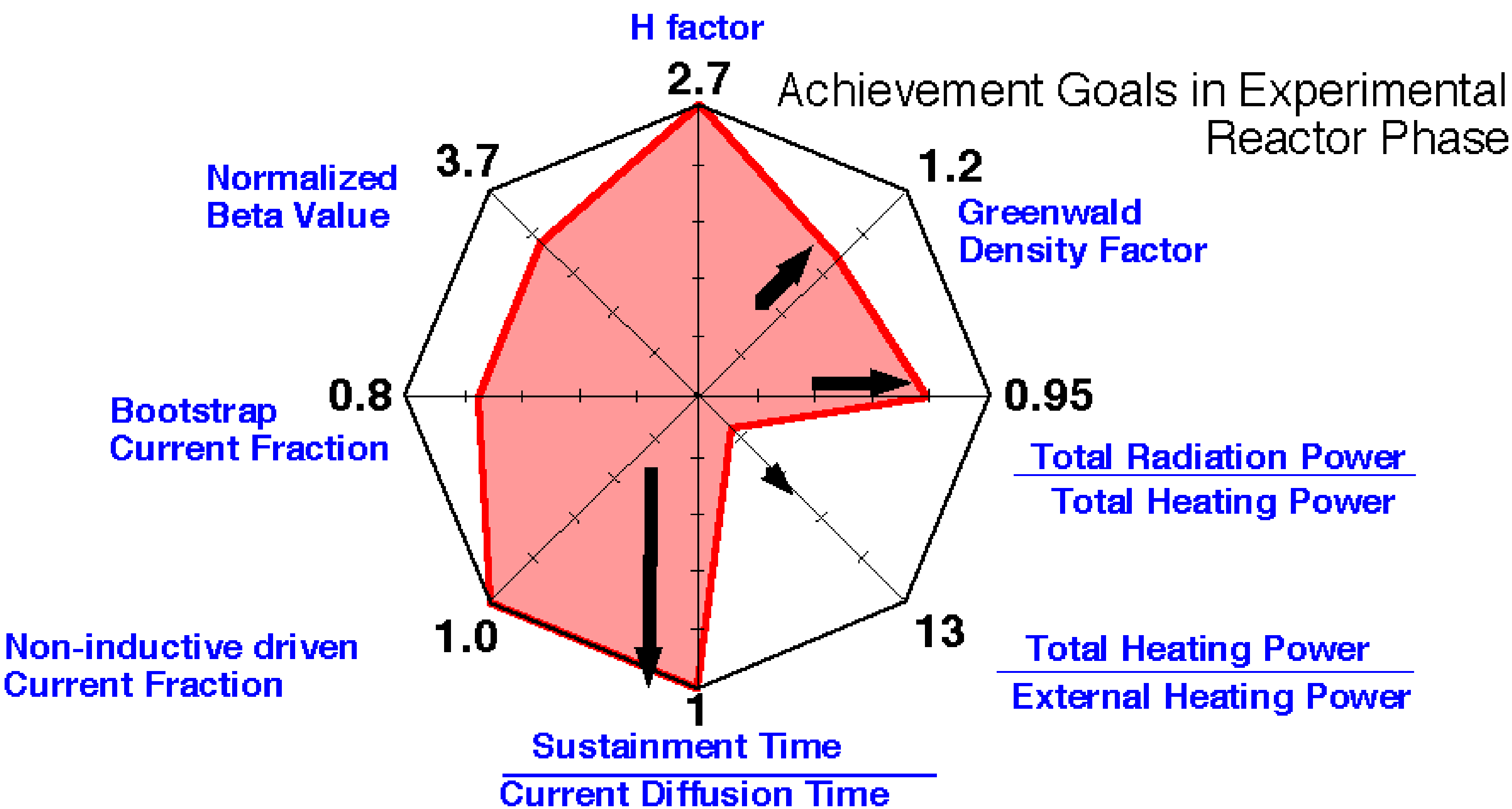
Required Advancement



Required Integrated Plasma Performance

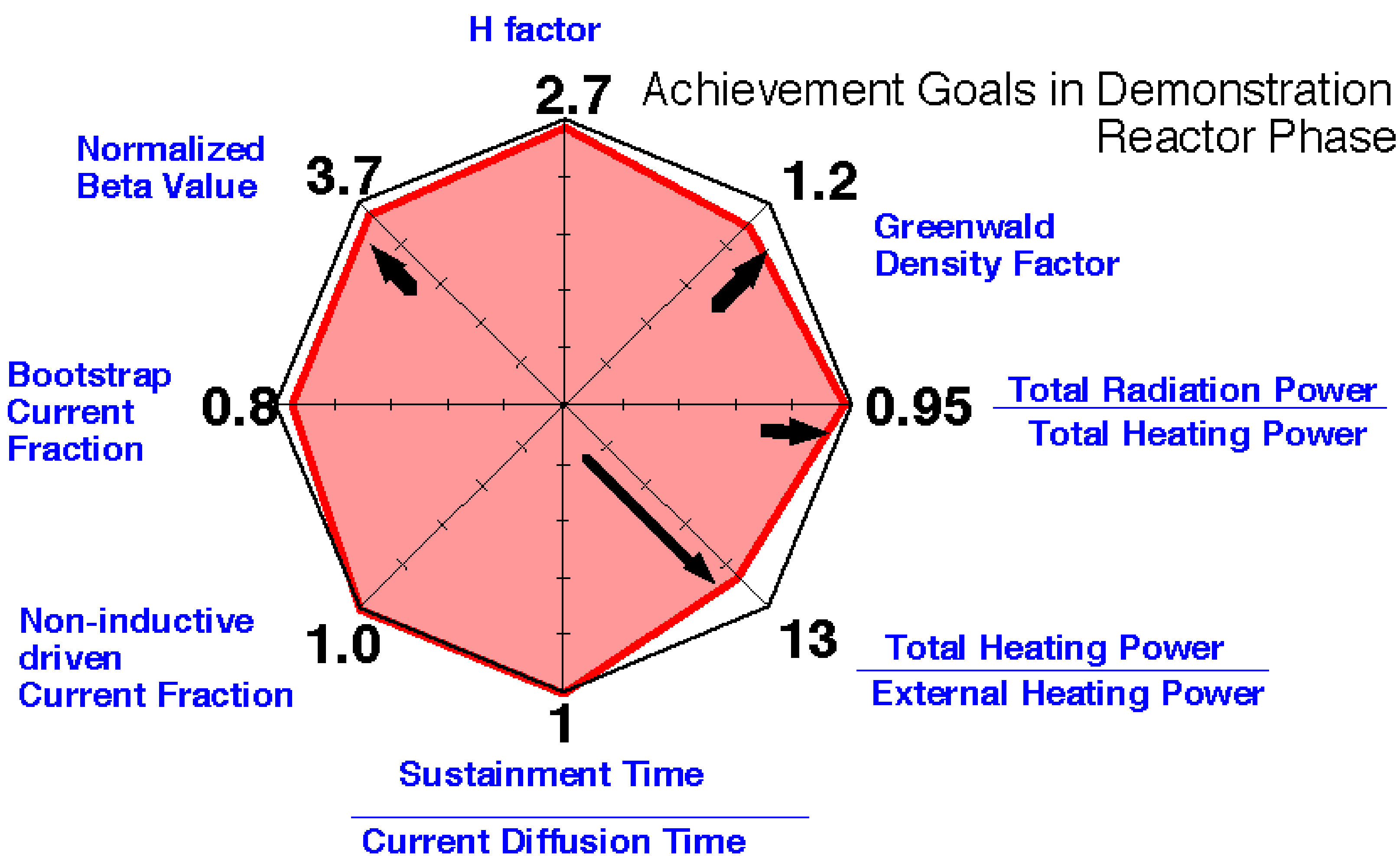


Status



H factor
2.7
Achievement Goals in Experimental Reactor Phase
3.7
Normalized Beta Value
1.2
Greenwald Density Factor
0.8
Bootstrap Current Fraction
0.95
Total Radiation Power / Total Heating Power
1.0
Non-inductive driven Current Fraction
13
Total Heating Power / External Heating Power
1
Sustainment Time / Current Diffusion Time

Status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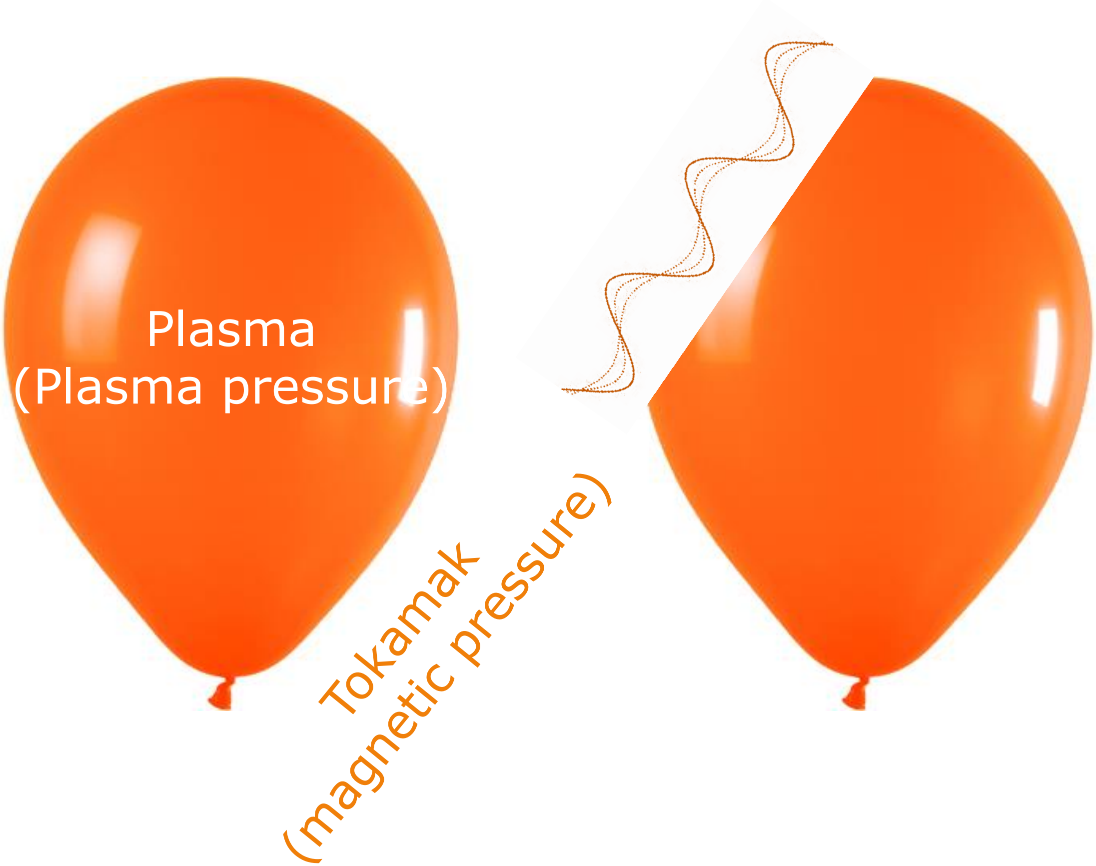
Sustainment Time
Current Diffusion Time

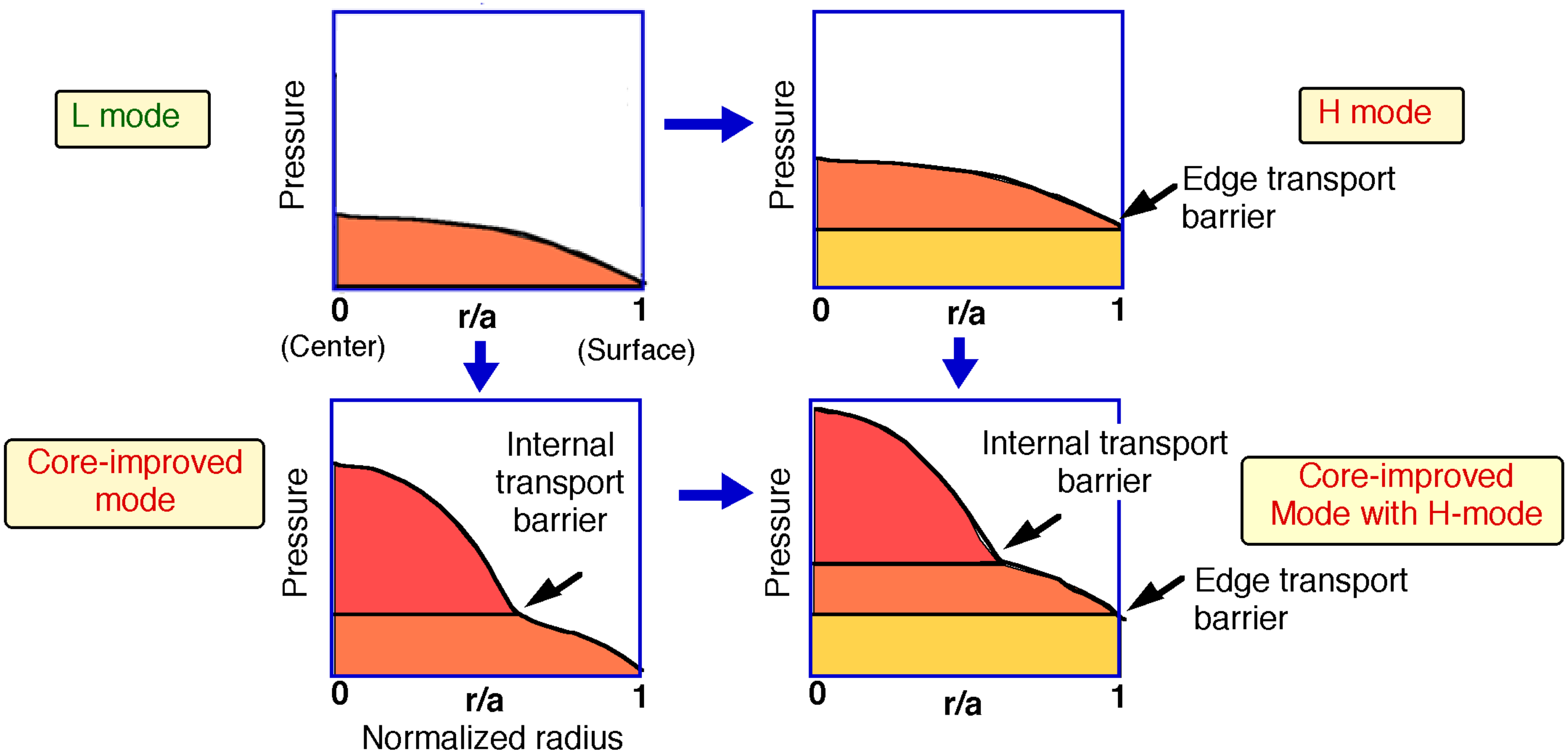
Issues and prospects for confinement performance

Plasma Equilibrium, Stability and Transport

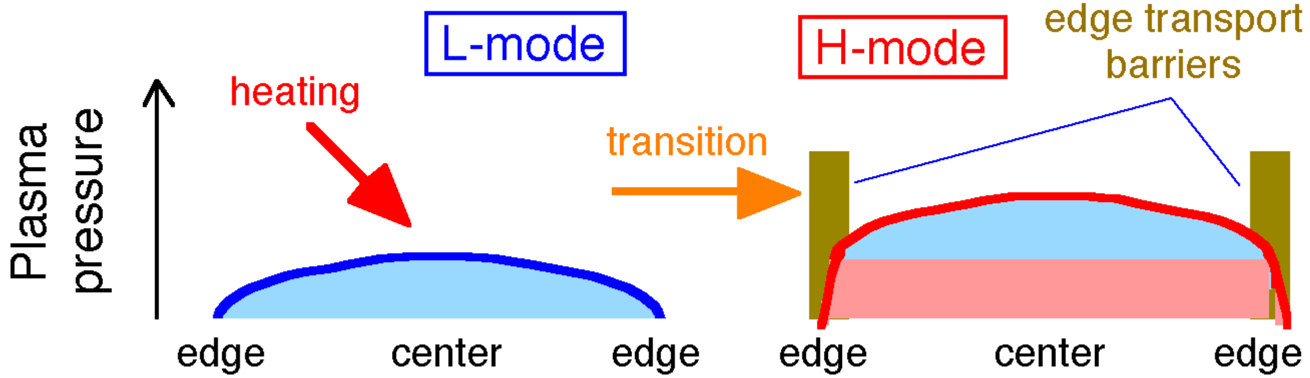


Plasma Transport – Confinment

Various Confinement Modes



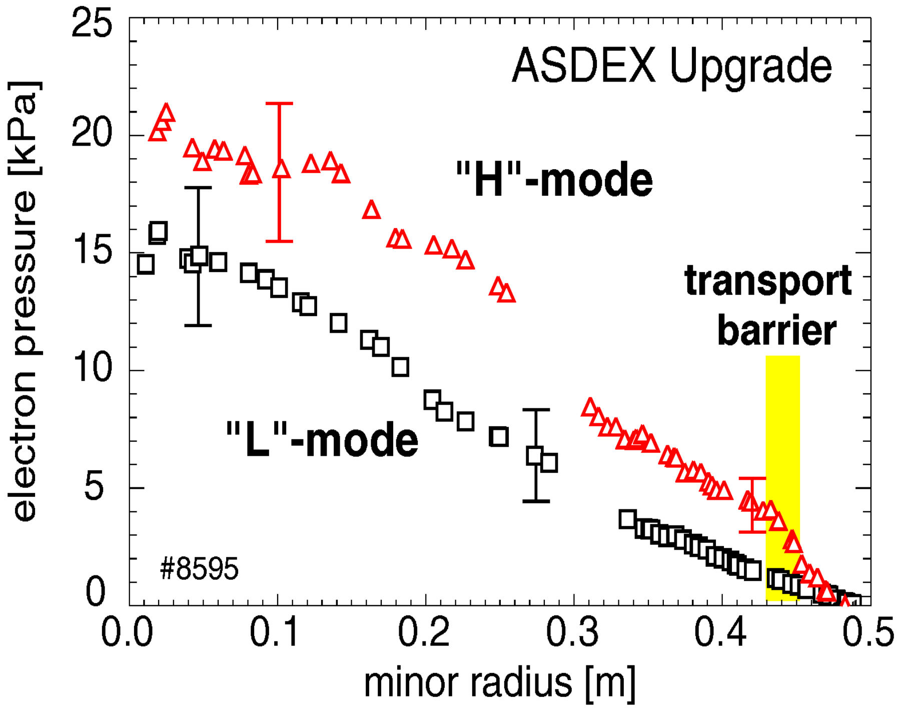
Energy Confinement



H-mode

- 1982 IAEA F. Wagner et al. (ASDEX, Germany)

- Transition to H-mode: state with reduced turbulence at the plasma edge
- Formation of an edge transport barrier: steep pressure gradient at the edge



Hoover dam

H-mode

- 1982 IAEA F. Wagner et al. (ASDEX, Germany)

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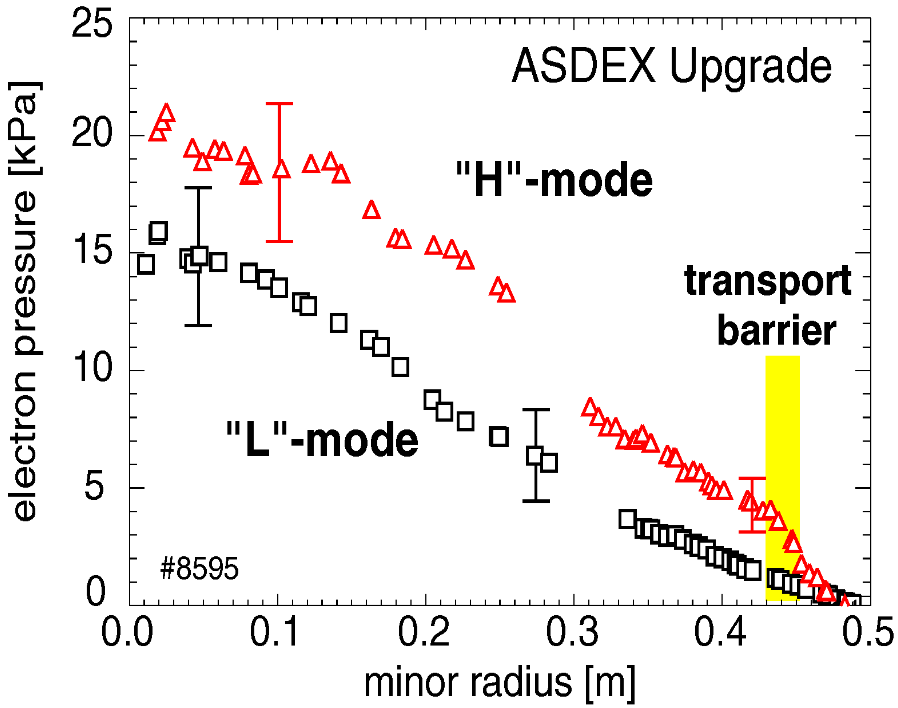

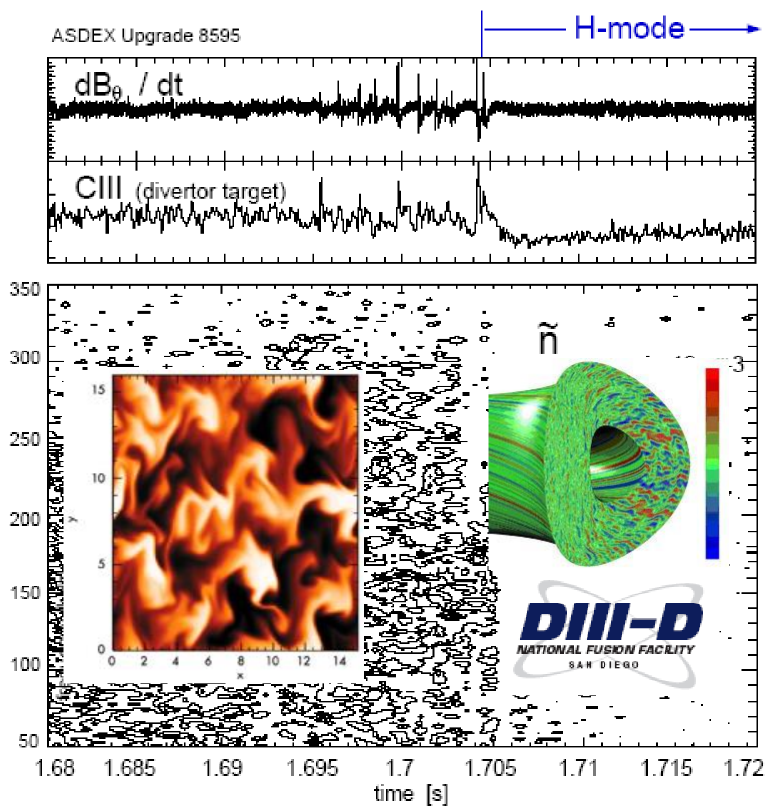

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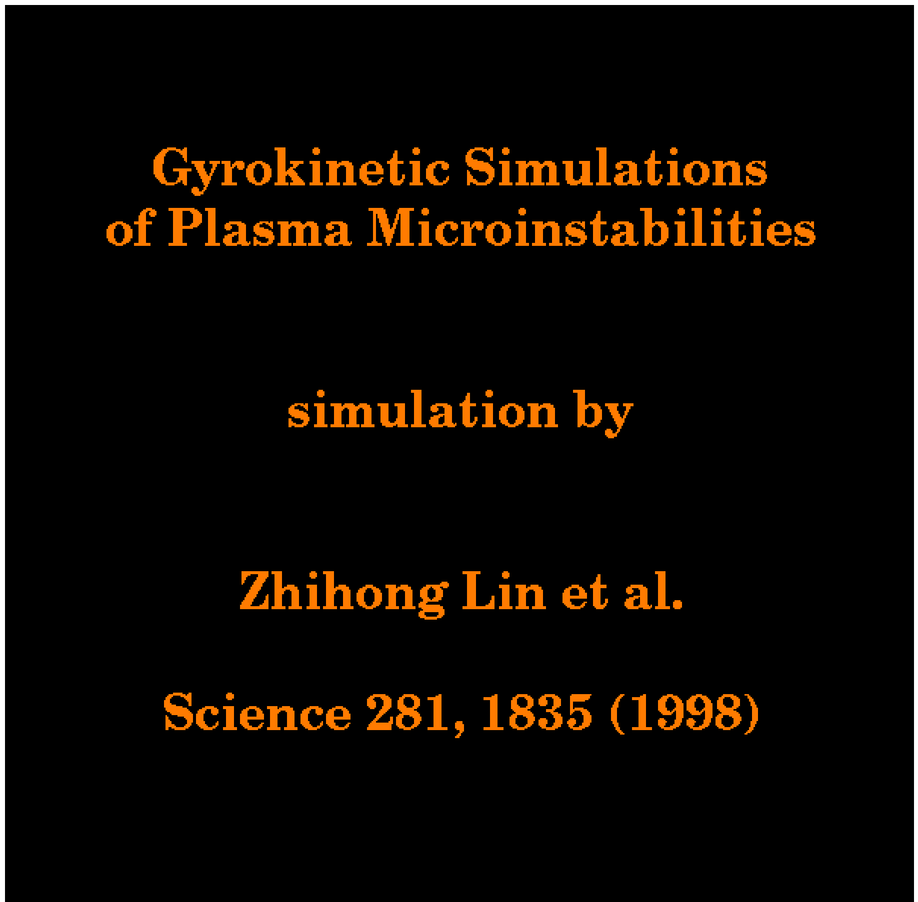
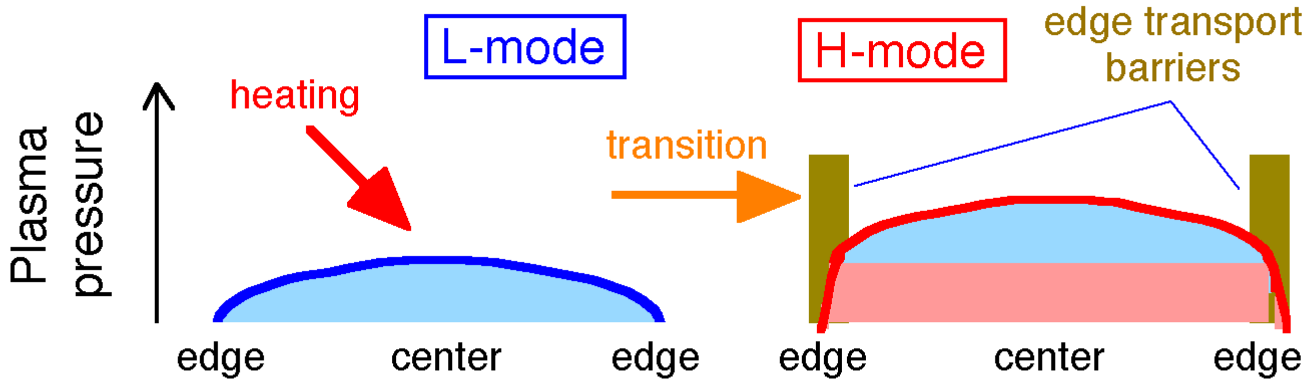


Confinement scaling



$\tau_E^{ITER89P} = 0.048 M^{0.5} I_p^{0.85} B_t^{0.2} R^{1.2} a^{0.3} \kappa^{0.5} n_{20}^{0.1} P^{-0.5}$ **M for DT mixture?**

$$\chi \sim \frac{a^2}{\tau_E} \sim \chi_{Bohm} (\rho^*)^{\mu} F(\beta, \nu^*)$$: nearly "Bohm" scaling (μ ~ 0)

Why?

$$\chi_{Bohm} = \frac{cT}{eB} \qquad D_\perp = \frac{1}{16}\frac{kT_e}{eB}$$

$\tau_{E,th}^{IPB98(y)} = 0.0365 M^{0.2} I_p^{0.97} B_t^{0.08} R^{1.7} a^{0.23} \kappa_a^{0.67} n_{19}^{0.41} P^{-0.63}$

$\propto \tau_B \rho^{*-0.83} \beta^{-0.50} \nu^{*-0.10} M^{0.97} q^{-2.52} \varepsilon^{-0.55} \kappa_a^{2.72}$

$$\chi \sim \frac{a^2}{\tau_E} \sim \chi_{Bohm} (\rho^*)^{\mu} F(\beta, \nu^*)$$: close to "gyroBohm" scaling (μ ~ 1, $\tau_E/\tau_B \propto \rho^{*-1}$)

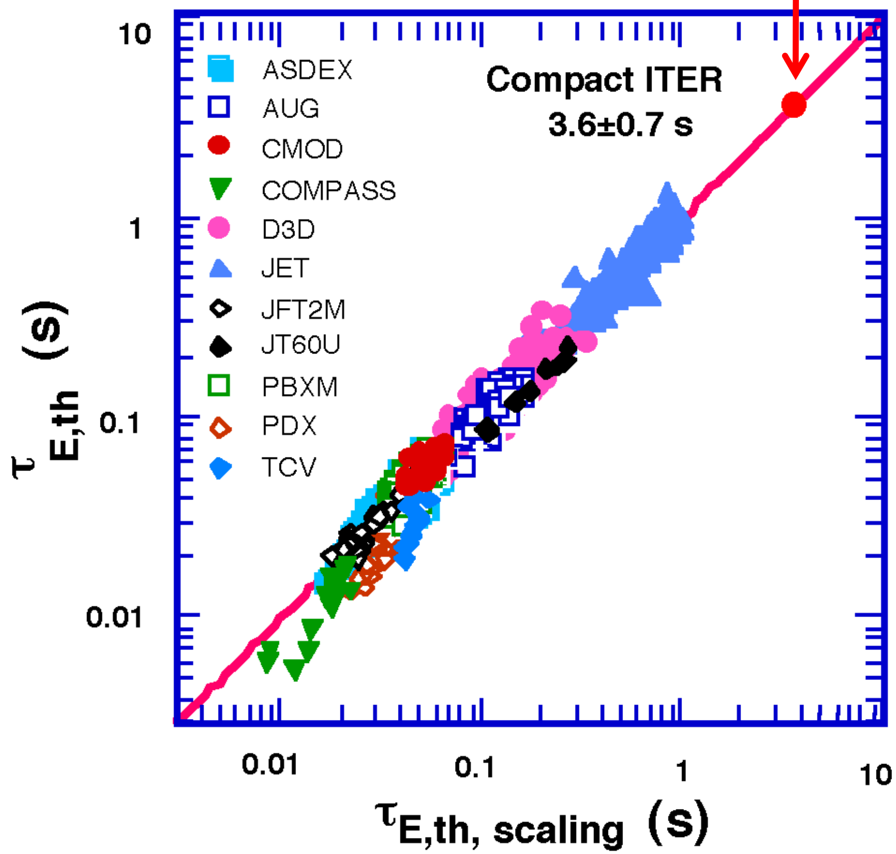
$$\chi \sim \left(\frac{\rho_i}{L}\right)\left(\frac{cT_i}{eB}\right) \qquad \left(\frac{\rho_i}{L}\right) << 1$$

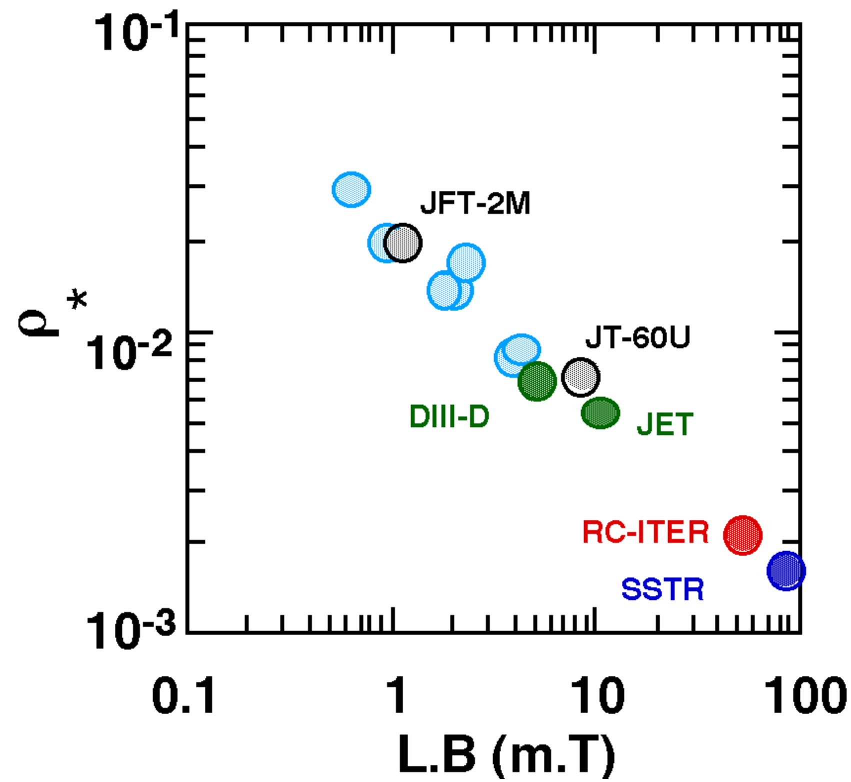
Confinement scaling

- ρ* 값이 작은 ITER나 원형로에서의 기존 토카막에 비한 밀폐 개선 기대
- ρ* 의존성의 과대 평가를 피하기 위해, 소형 장치(big ρ*) 생략한 IPB98(y, 2) 구축

$$\tau_{E,th}^{IPB98(y,2)} = 0.0562 M^{0.19} I_p^{0.93} B_t^{0.15} R^{1.39} a^{0.58} \kappa_a^{0.78} n_{19}^{0.41} P^{-0.69}$$

$M=2.5,\ I_p=15MA,\ B_t=5.3T,\ R=6.2m,\ a=2.0m,\ \kappa_a=1.75,\ n_{19}=10,\ P=90MW$



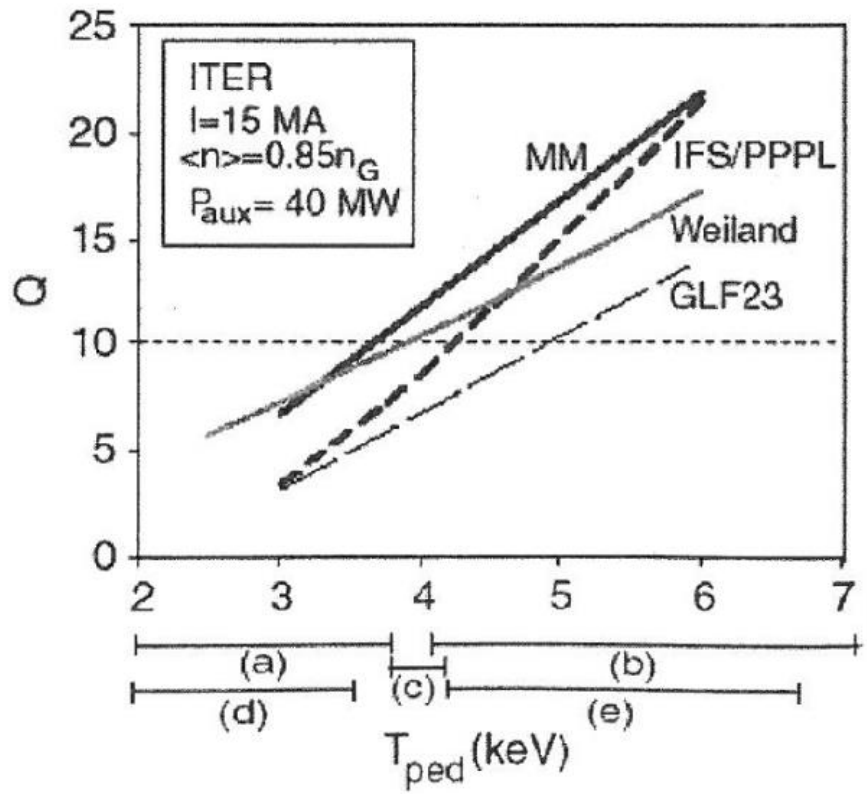


Confinement scaling

- 플라즈마의 축적 에너지를 pedestal 성분과 core 성분으로 나눈 scaling law

$$\tau_{E,th}^{ONL} = 0.082 I_p B_t R a \kappa P^{-1} b^{-0.1} + 0.043 I_p^{0.6} n_{19}^{0.6} R^{1.3} a P^{-0.4} b^{-0.15}$$

$$b = B_t R^{1.25}$$

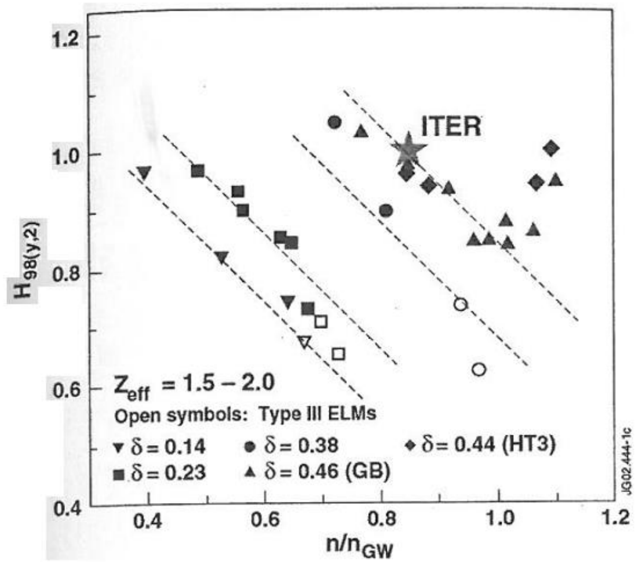


Confinement scaling

- **Scaling law의 한계점**

- 이온 가열이 주가 되는 데이터가 많이 포함되어 있음.
Cf. 원형로에서는 α 가열 주체로 인해 전자 가열이 주가됨. 전자계와 이온계에서의 난류 수송 기구가 다름 → 전자 가열이 주가 되는 경우에 대해서도 비례칙이 성립함을 넓은 파라미터 영역에서 확인해야 함.

- 고밀도 운전에 대한 데이터가 많이 포함되어있지 않음: 고밀도 운전에 대한 바람직한 의존성을 보임. 실험에서는 Gas puffing을 통한 밀도 증가는 밀폐 성능을 악화시킴. 플라즈마 형상의 영향에 대한 데이터베이스 확보 필요



L-H transition threshold power

- **Experiment**

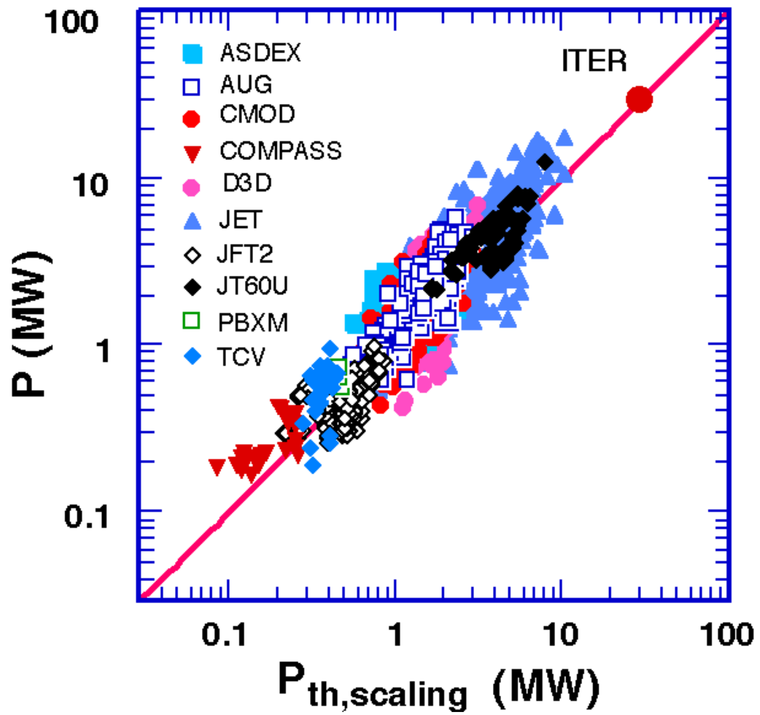
- Good wall-condition: low impurity content, low recycling
- Enough heating power

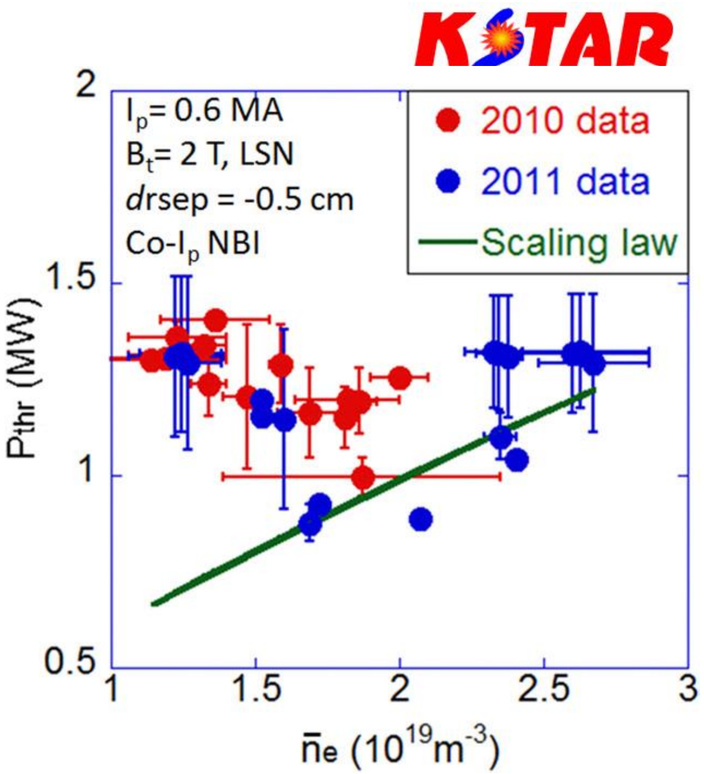
- **Theory: ExB shear**

- Origin of the radial electric field
  (1) Reynolds stress
  (2) Ion orbit loss
  (3) Stringer spin-up

L-H transition threshold power

$P_{th} = 2.84M^{-1}B_t^{0.82}n_{20}^{0.58}R^{1.0}a^{0.81}$





$$P_{thr,scaling} = 0.0488 \pm 0.0028 n_{e20}^{0.717\pm0.035} B_T^{0.803\pm0.032} S^{0.941\pm0.019}$$

Y. R. Martin et al., J. Phys.: Conf. Ser. ***123*** *012033 (2008)*
J-W. Ahn, H.-S. Kim et al., Nucl. Fusion ***52*** *114001 (2012)*

L-H transition threshold power

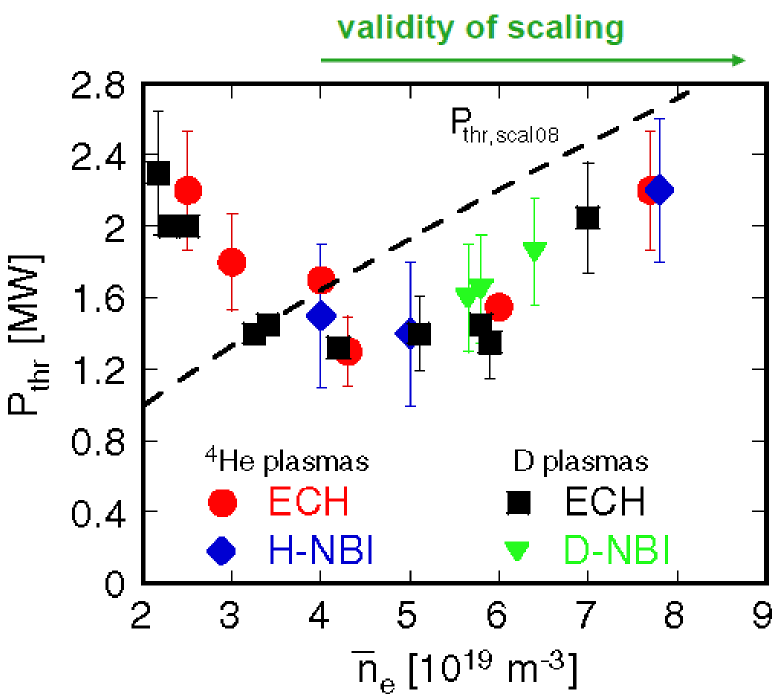
Progress in R&D - H-mode Access

Helium H-modes

- **Access to type-I ELMy H-modes during the non-active phase would have a significant impact on the ITER Research Plan:**
  - would allow, e.g., investigation and demonstration of ELM control
  - impacts on divertor changeout and deuterium operation ⇒ accelerates progress towards DT plasmas
- **AUG finds: P_{thresh} (He) ~ P_{thresh} (D)**
- **JET finds:**

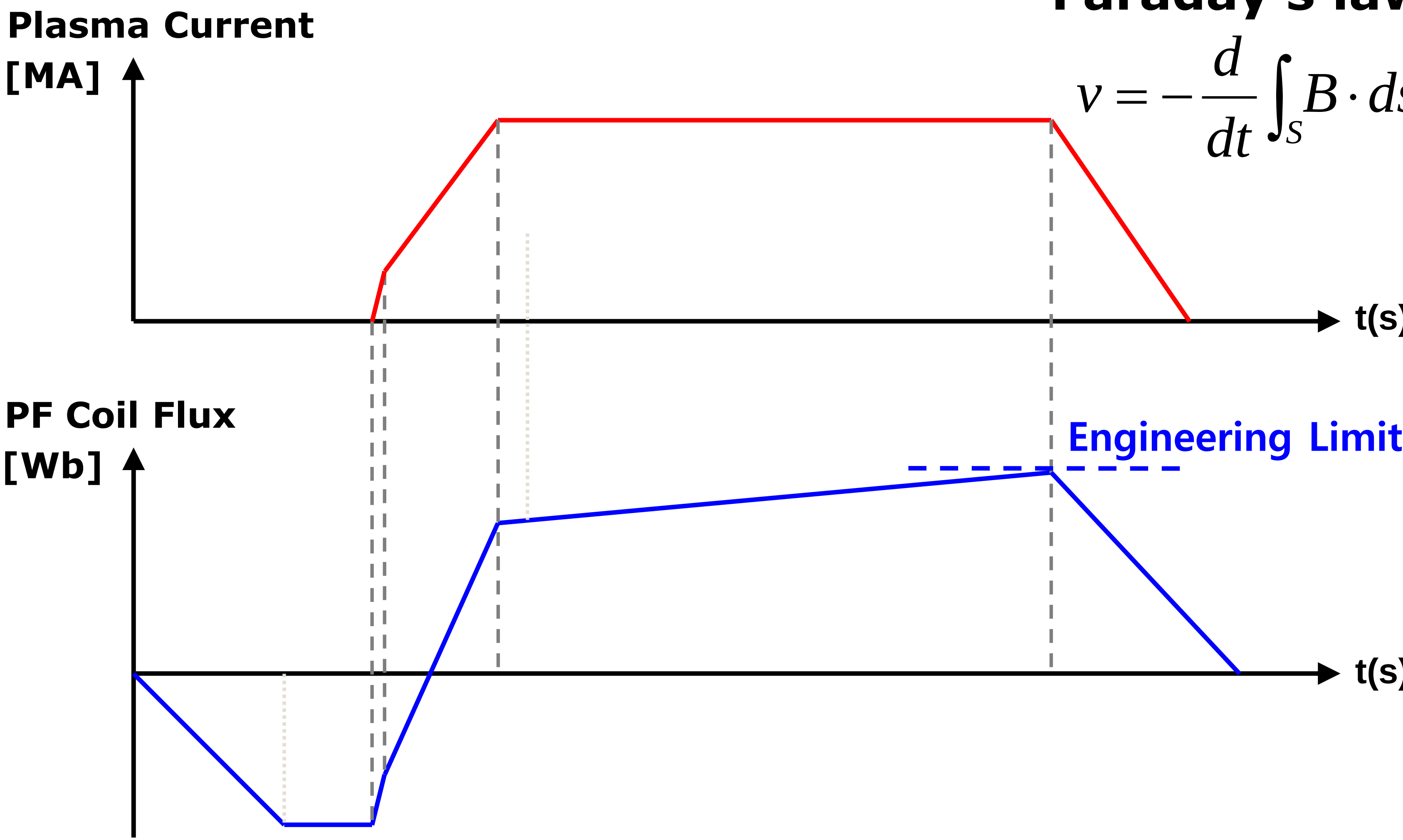
  P_{thresh} (He) ~1.4 – 1.5 P_{thresh} (D)
- **Recent C-Mod results find: 1.2 < P_{thresh}(He)/P_{thresh}(D) < 1.8**
- **More detailed studies are required**

ASDEX Upgrade Results



F Ryter et al, NF (2009) 062003

H-mode: Limitation

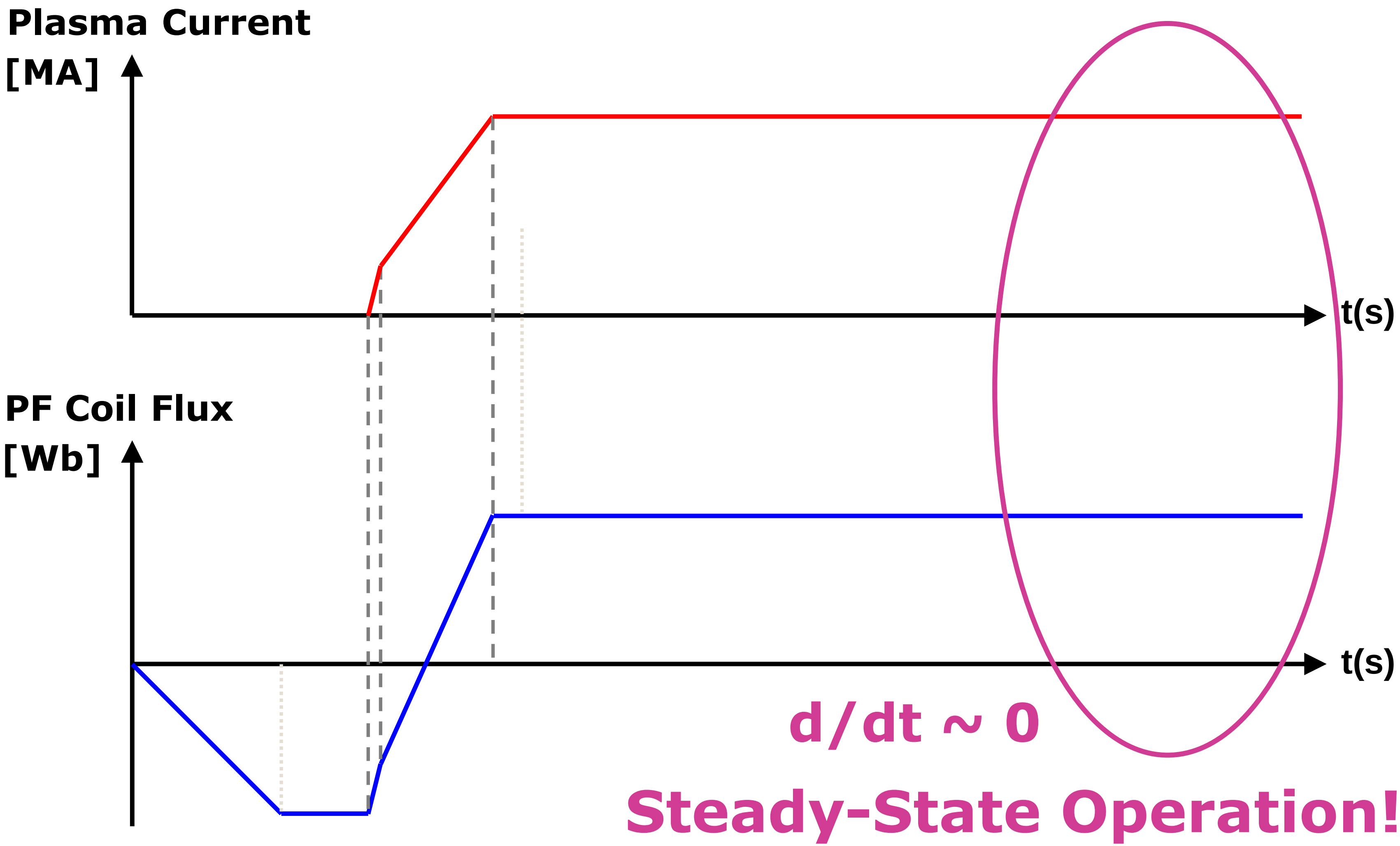


Faraday's law

$$v = -\frac{d}{dt}\int_S B \cdot ds$$

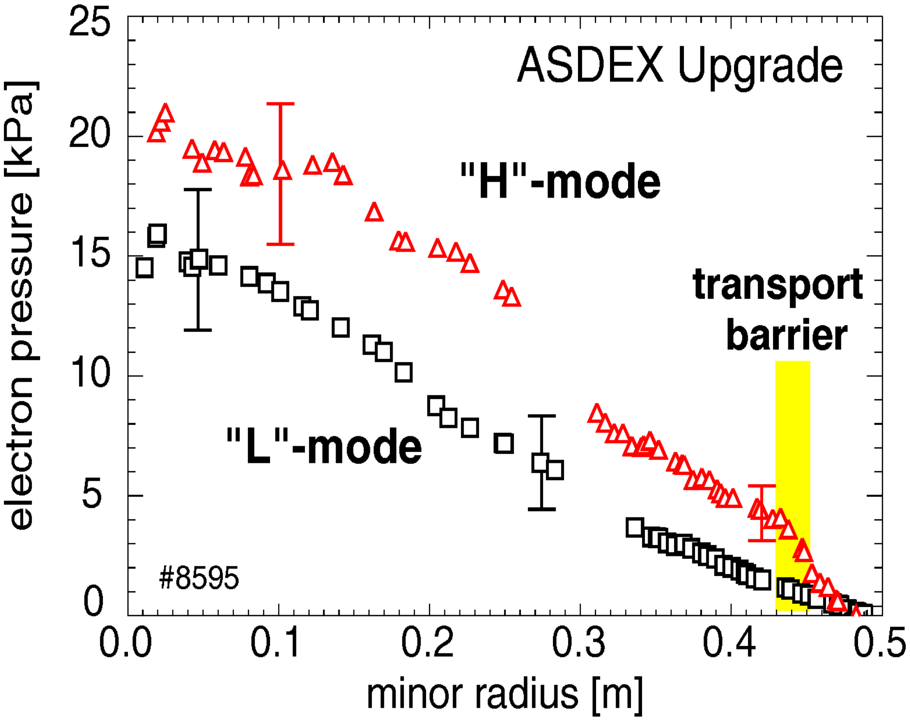
Inherent drawback of Tokamak!

Improved confinement suitable for the steady-state operation

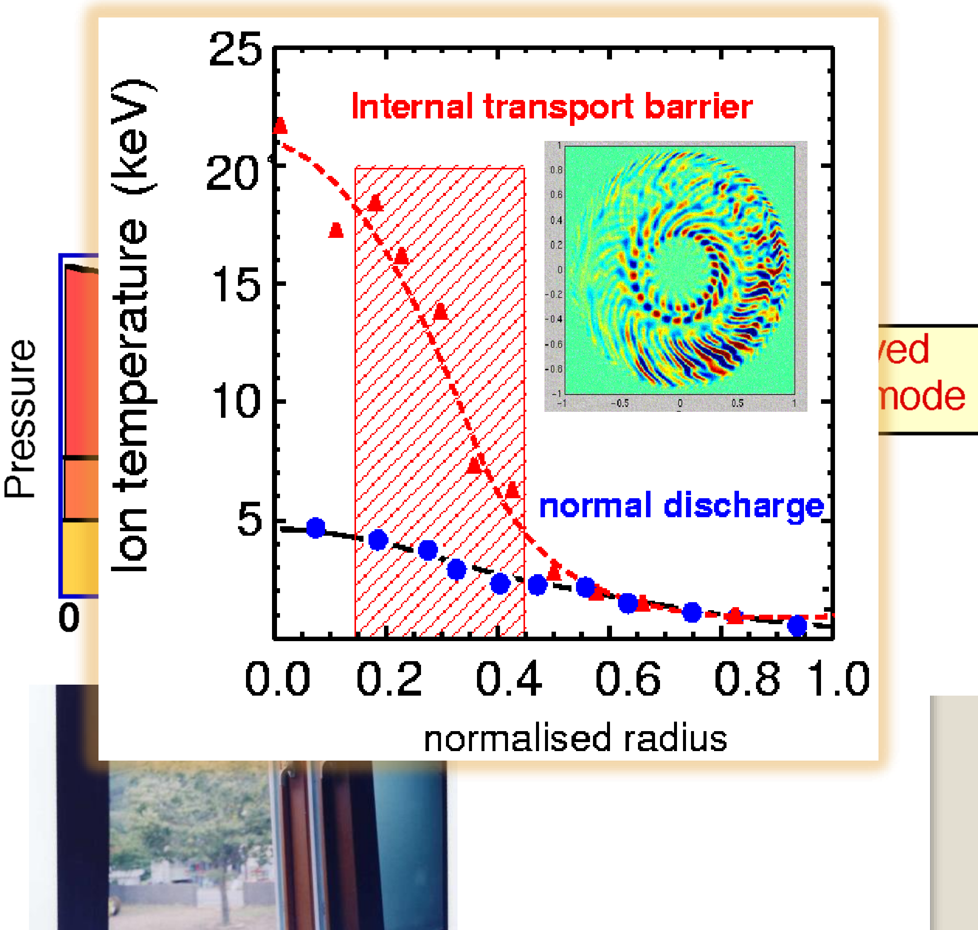


ITB

H-mode



Reversed shear mode



ITB

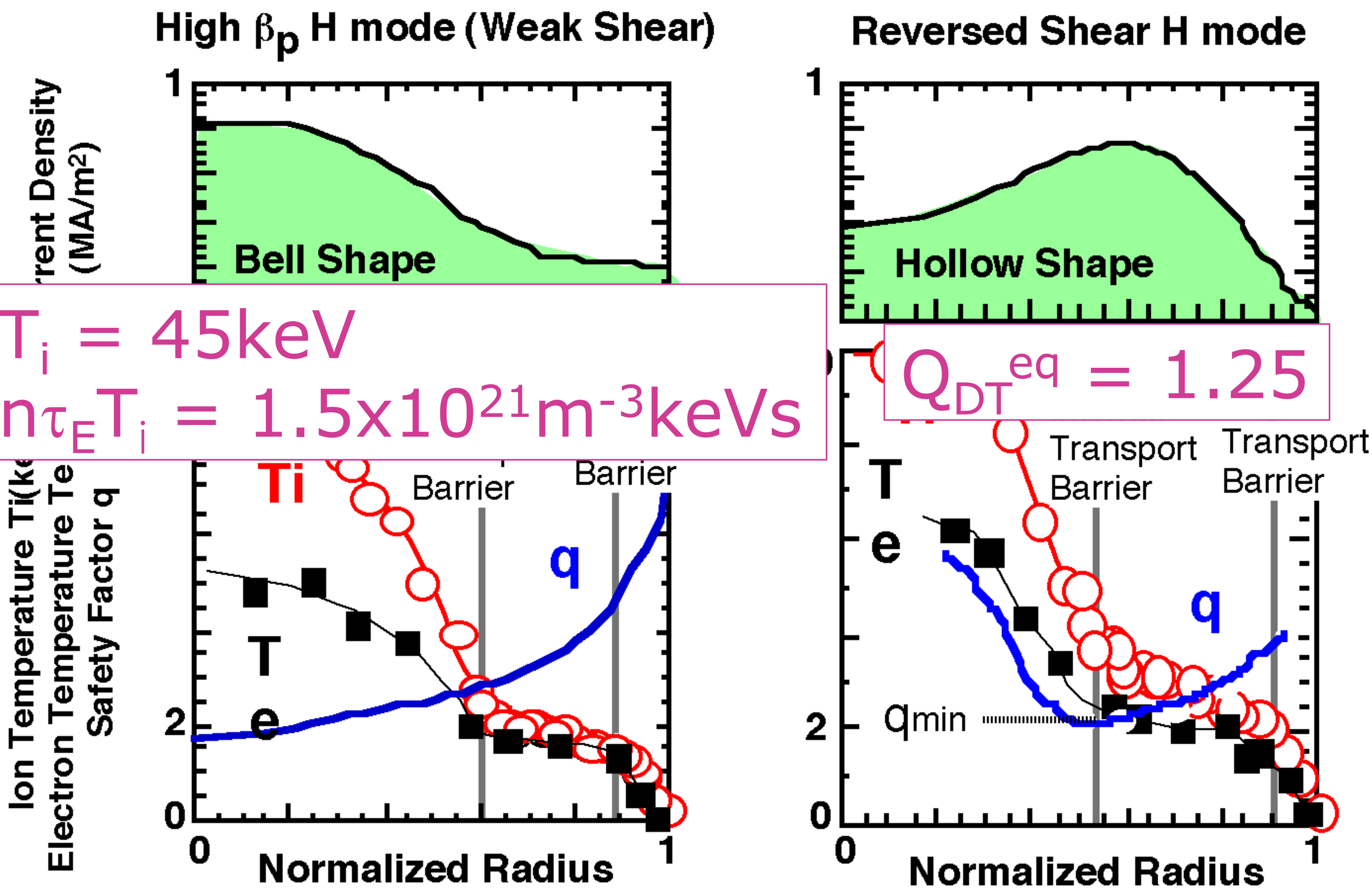
- **ITB plasmas의 원형로 설계를 위한 과제**

- 밀폐 비례칙의 확립:

ITB 플라즈마에 대해서도 scaling law 구축의 중요성은 인식되며, 밀폐 성능이나 threshold power의 scaling law 구축을 목적으로, global(0-D) database가 ITPA에서 구축되고 있음.
하지만 ITB는 다양한 분포 구조를 가지고 있다는 것과, 그 특성은 국소물리량에 크게 영향을 받기 때문에, 경계 수송에서 전체의 밀폐가 거의 정해져 버리는 H 모드에 비해, scaling law 구축이 어려움.

- ITB 형성 조건 혹은 threshold power scaling law의 확립
- 수송 모델 확립

ITB

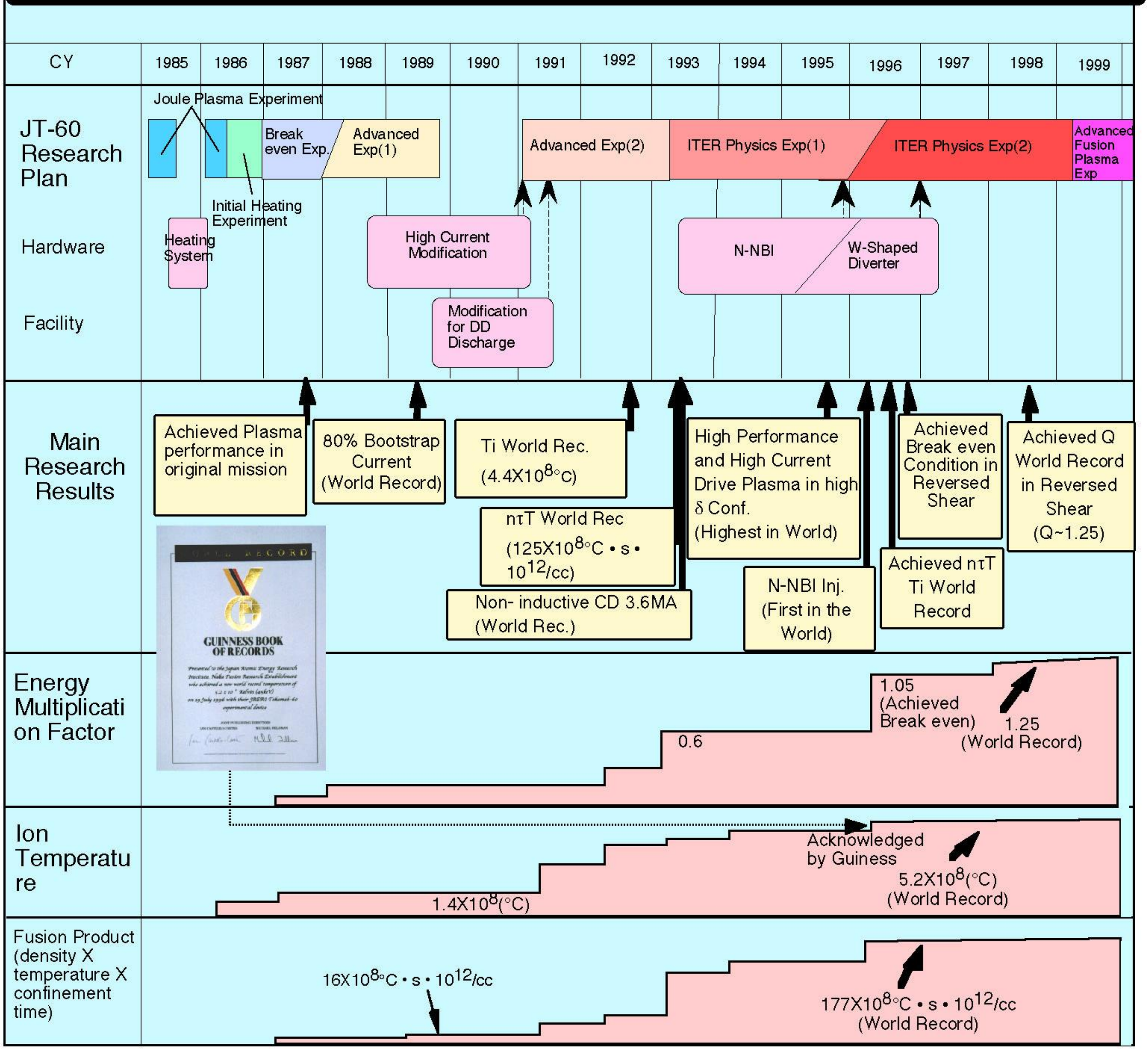


T_i = 45keV

$n\tau_E T_i$ = 1.5x10^{21}m^{-3}keVs

Q_{DT}^{eq} = 1.25

Transition of JT-60 Program and Progress in Plasma Performances



Particle Confinement

- **Difficulties**

- 확산 계수뿐만 아니라 대류속도(convection pinch)를 고려해야 함.
- 리사이클링에 의한 입자원의 정량화가 어려움.

→ 열수송의 연구에 비해 그다지 활발하게 이루어지지 못하고 있음.

- **Pinch and density peaking**

- 신고전 이론에 따라 토로이달 전장에 의해 야기되는 Ware pinch 효과만으로는 정량적으로 설명되지 않음.
- 토로이달 전기장이 공간적으로 제로가 되는 조건 하에서도 명확하게 중심이 피크인 밀도 분포가 관측됨 (Tore Supra, TCV).
- Collisionality dependency가 발견됨: 난류의 수치 시뮬레이션에 의해 ITG나 TEM 등의 난류가 이상 내향 핀치를 일으키는 것으로 확인됨.

→ ITER에 외삽하면, 상정했던 flat profile 보다 30% 정도 핵융합 출력 증가

→ 밀도 분포는 핵융합 출력에 큰 영향을 주기 때문에,
(i) 밀도 분포를 결정하는 물리 기구의 해명과 예측,
(ii) 연소 제어로써의 밀도 분포 제어 수법의 확립 필요

Particle Confinement

- **Density peaking**

- Collisionality dependency가 발견됨: 난류의 수치 시뮬레이션에 의해 ITG나 TEM 등의 난류가 이상 내향 핀치를 일으키는 것으로 확인됨.

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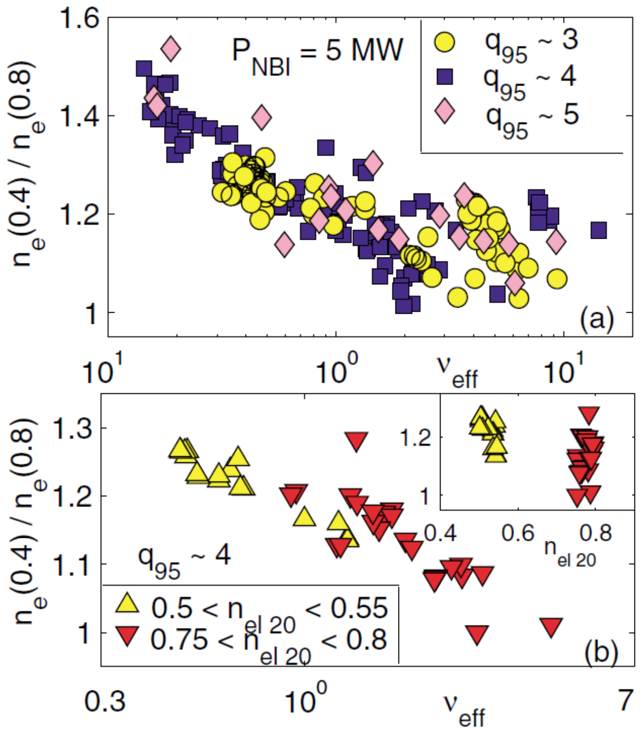
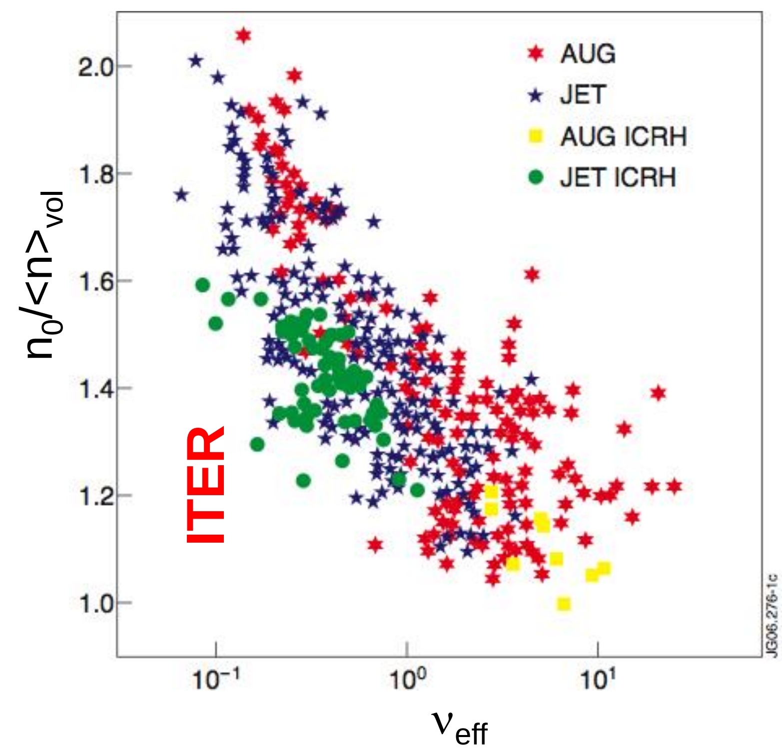


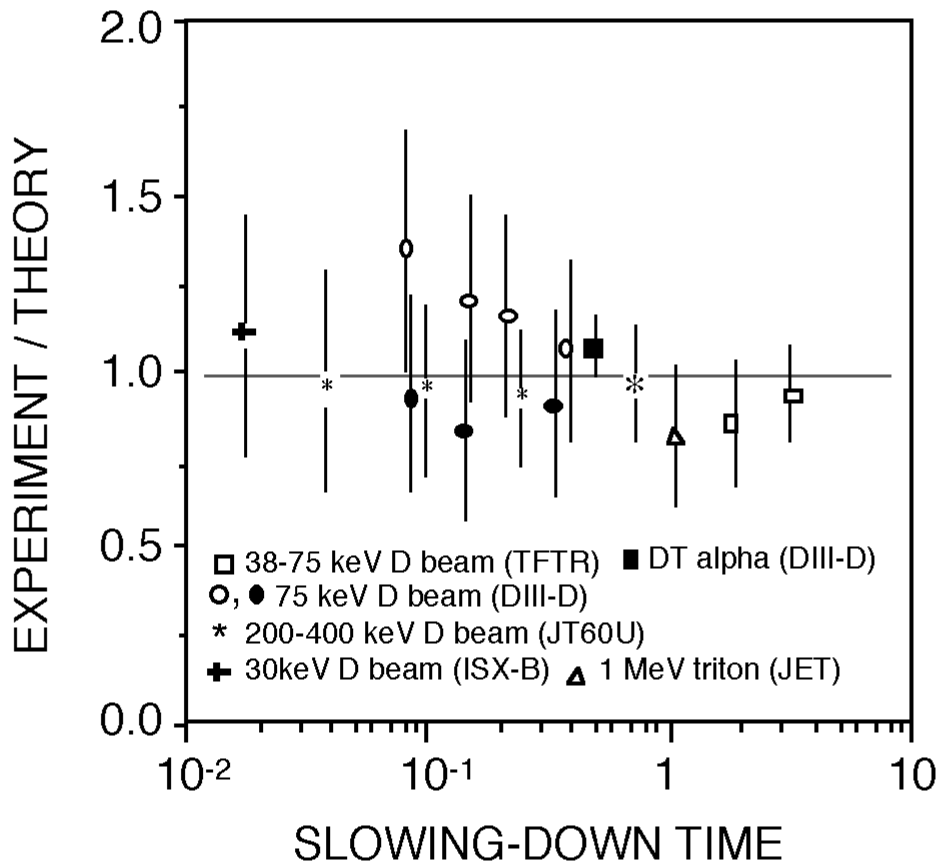
*C. Angioni et al., Phys. Rev. Letters **90** 205003 (2003)*



H. Weisen, IAEA FEC 2006

Confinement of energetic particles

- Transport of energetic particles (alpha particles)
  - Toroidal Ripple loss
  - Alfven eigenmodes (AE)
  - MHD instabilities



- The slowing-down time of energetic ions agrees well with Neoclassical estimate.

- The diffusion coefficient of energetic particles is consistent with the NC model.
  - orbit averaging
  - Small TAE due to small β_α

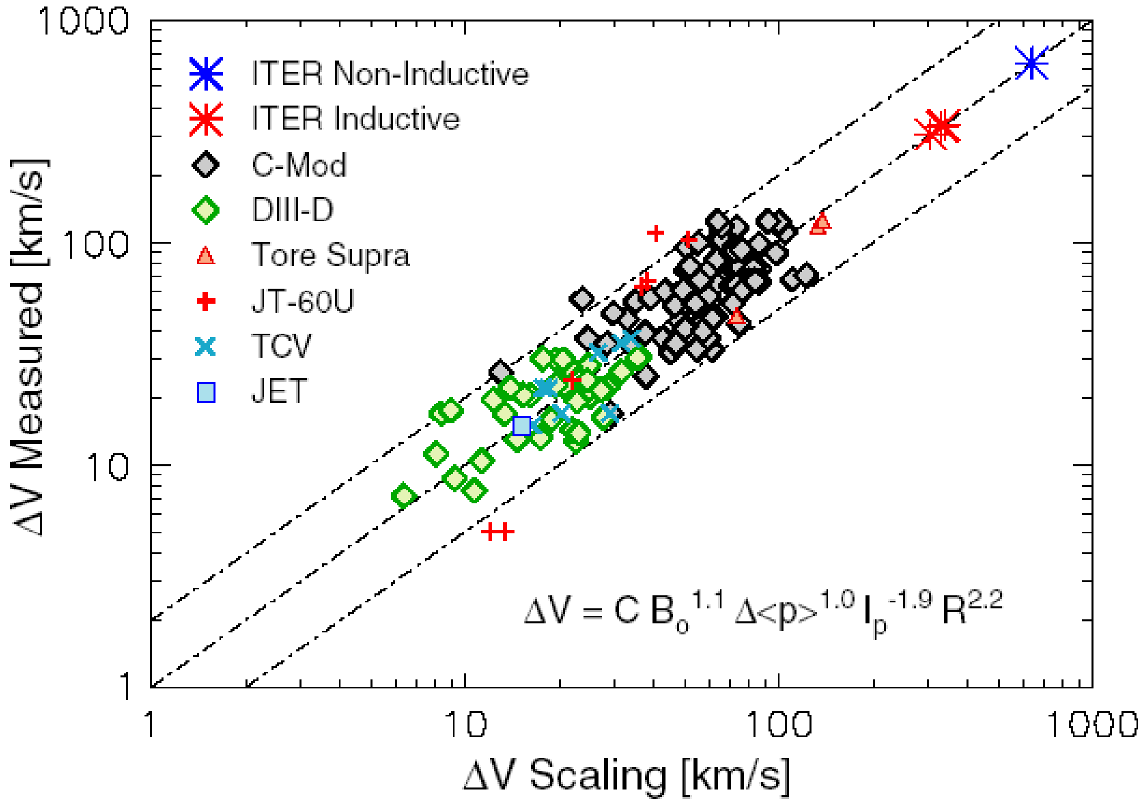
Momentum Transport

- **Intrinsic rotation**

- **Toroidal rotation의 장점:**
  (1) 난류 수송 억제에 의한 수송 장벽 형성에 기여
  (2) RWM 억제에 의한 자유 경계 베타 한계를 초과한 운전 영역 access
- ITER나 원형로에서는 외부 actuator로부터의 운동량 입사가 적어서 충분한 토로이달 회전을 얻을 수 없다고 생각되었음.
- Intrinsic rotation의 발견과 원인
  (1) Residual stress
  (2) 압력 구배 구동
  (3) 신고전 토로이달 점성 토크
  (4) 이온 궤도 손실
  (5) jxB torque

Momentum Transport

- **Intrinsic rotation**



J. E. Rice *et al*, *Nucl. Fusion* **47** 1618 (2007)

Momentum Transport

- **Inward pinch**

- JT-60, JET, DIII-D에서 얻어진 운동량 핀치의 분포 형상이 매우 유사 (수십 m/s 정도)
- 이론과 일치

$$V_{conv}^{TEP} \cong -\frac{2F_{balloon}}{R_0}\chi_\phi$$

T.S. Hahm et al., PoP **14**, 072302 (2007)

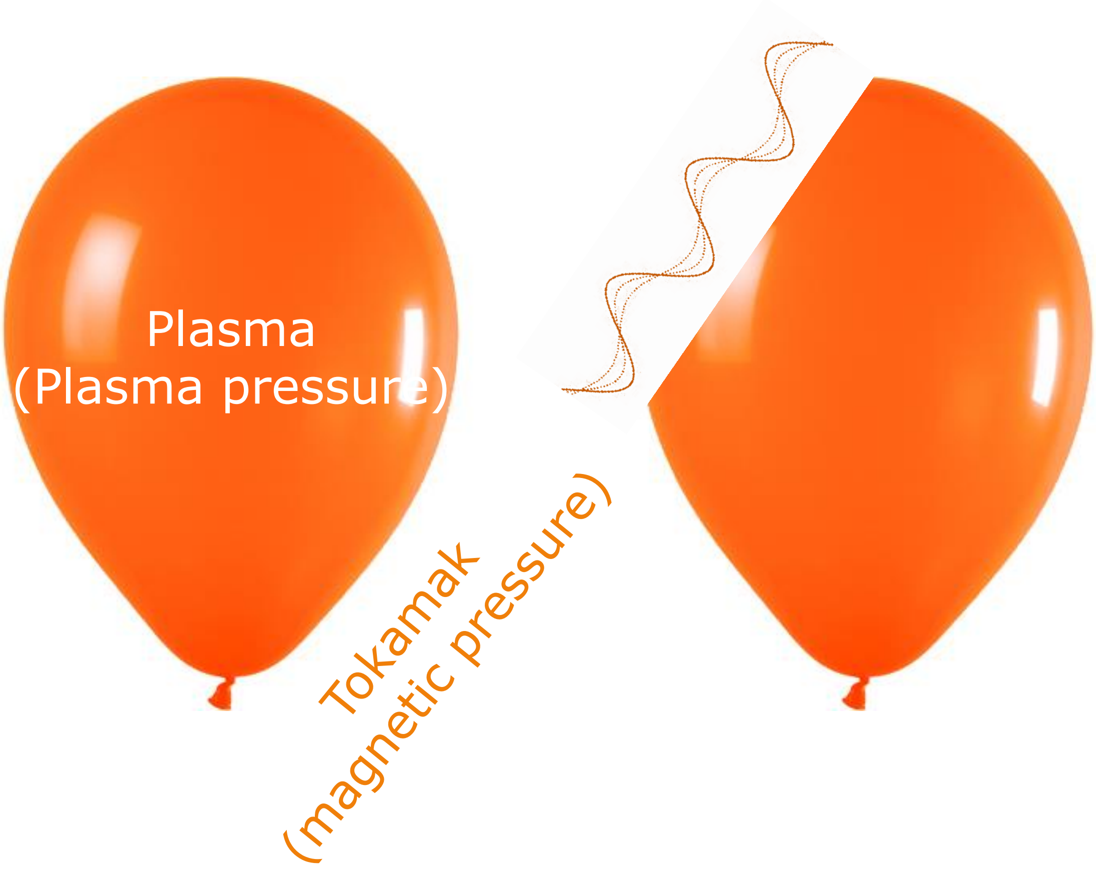
$$\frac{V_p}{\chi_\phi} = -\frac{1}{L_n} - \frac{T_i}{T_e}\frac{4}{R}$$

A.G. Peeters et al., PRL **98** 265003 (2007)

$$\frac{V_p}{\chi_\phi} = \frac{1}{L_n} - \frac{\left(\frac{5}{2} - \alpha_c\right)}{L_{T_i} T_e} - \frac{8}{5}\frac{\alpha_c}{R}$$

E.S. Yoon and T.S. Hahm, NF **50** 064006 (2010)

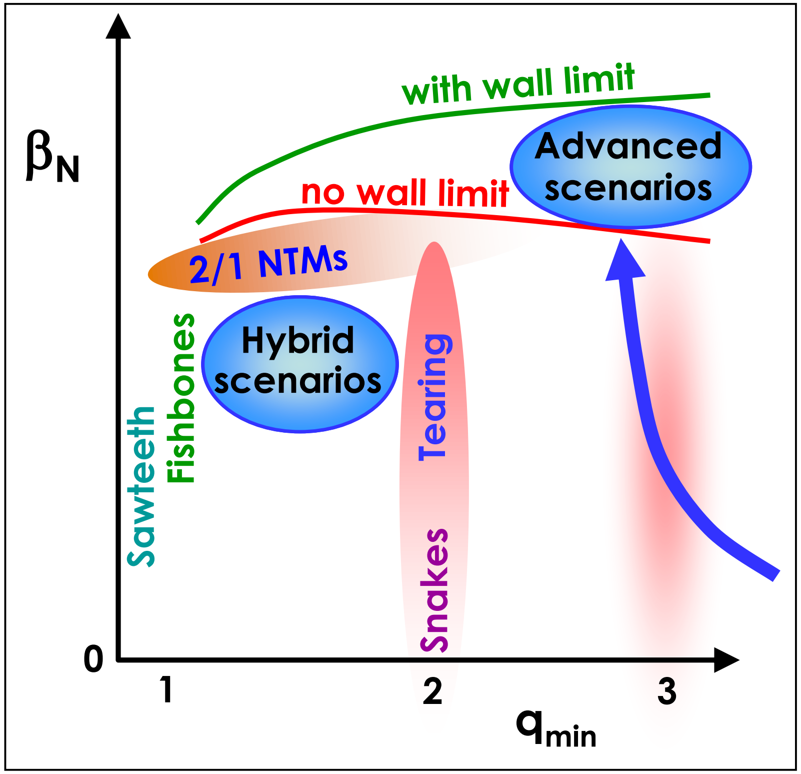
Plasma Stability



MHD stability issues

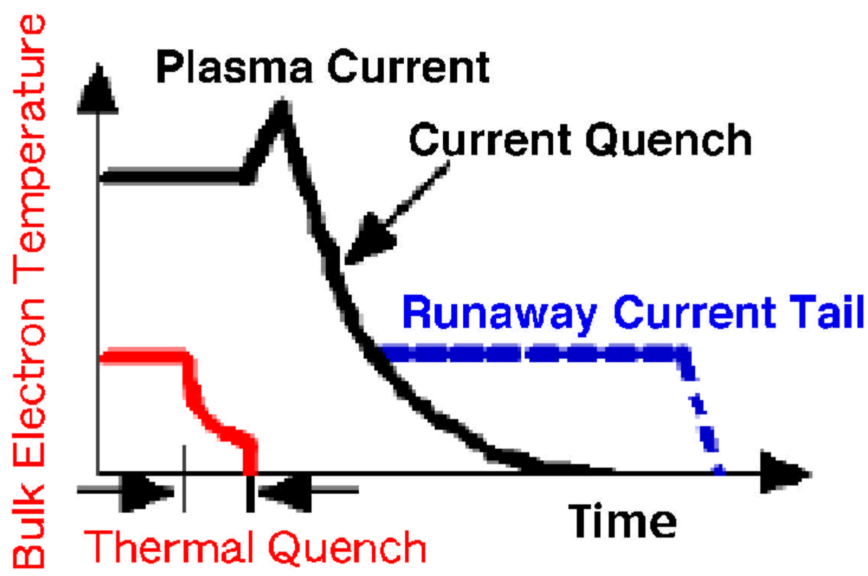
- Edge Localized Modes
- Damage to Plasma Facing Components
- Neoclassical tearing modes
- Limiting pressure, risk of disruption
- Resistive wall modes
- Limiting pressure
- Disruptions
- Device safety
- Fast particle modes
- Limiting α-heating, CD

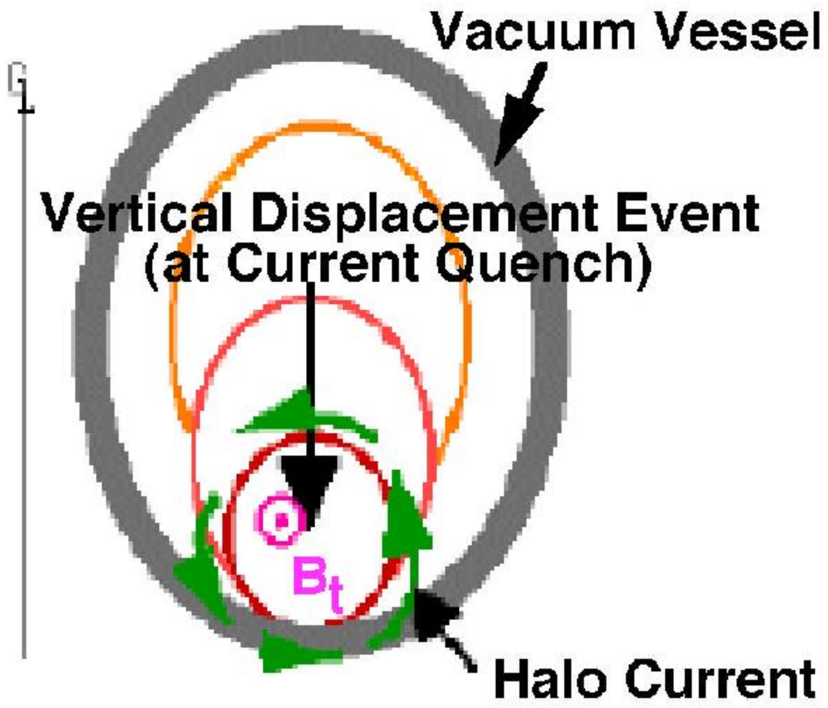
→ Real Time
feedback control required



R. Buttery, EFPW 05

Disruption control

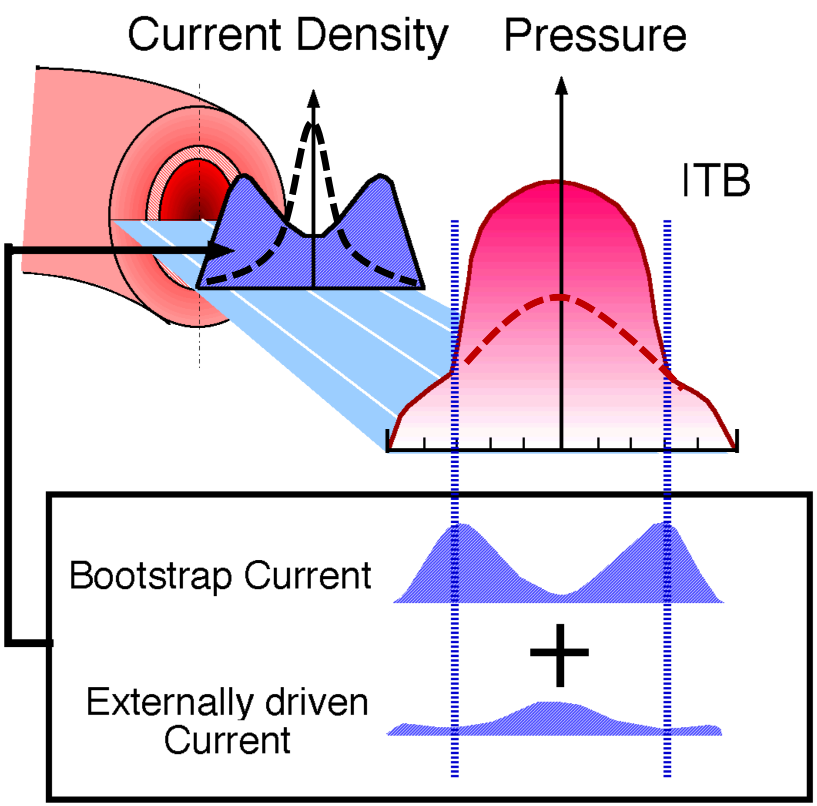




- Injection of neon ice pellet: fast conversion of thermal energy to the radiation energy
- $q < 2$: runaway electrons not produced due to instabilities
- Possible disruption events in the process of the optimisation of operation scenarios, fault operation, failures in hardware, or an emergency interrupt triggered by the safety interlock → 0.5#/year

Issues and prospects towards steady-state operation

Current drive and current profile control



Non-monotonic current profile

↓

Turbulence suppression

↓

High pressure gradients

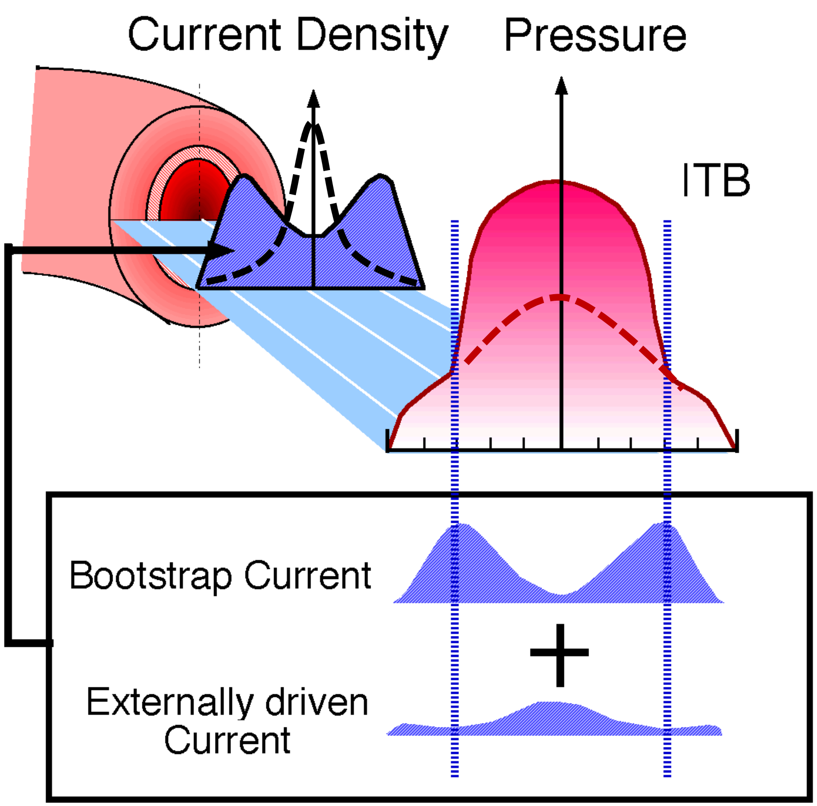
↓

Large bootstrap current

↓

Non-inductive current drive

Current drive and current profile control



Cf. NTM control

Non-monotonic current profile

↓

Turbulence suppression

↓

High pressure gradients

↓

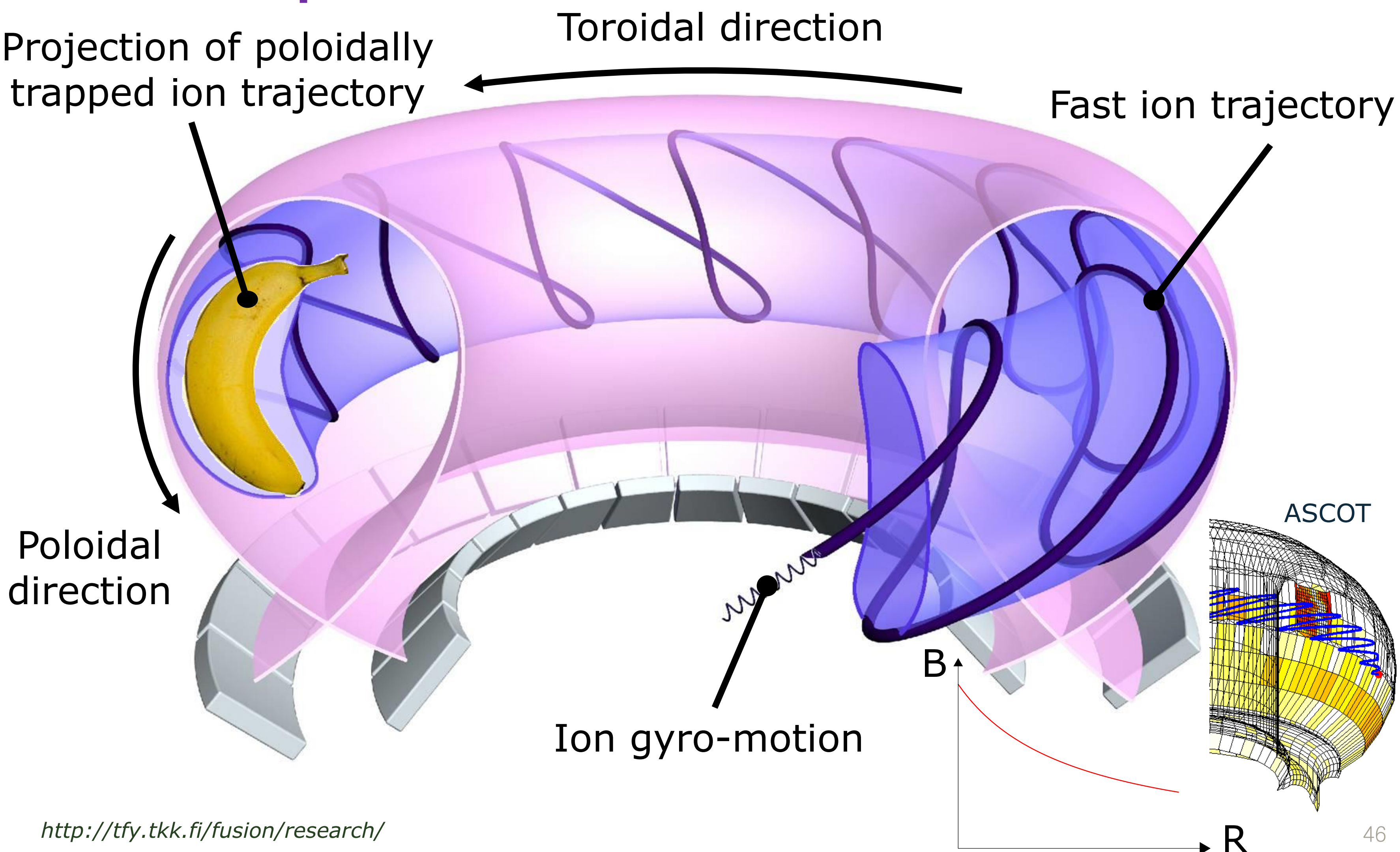
Large bootstrap current

↓

Non-inductive current drive

Current drive and current profile control

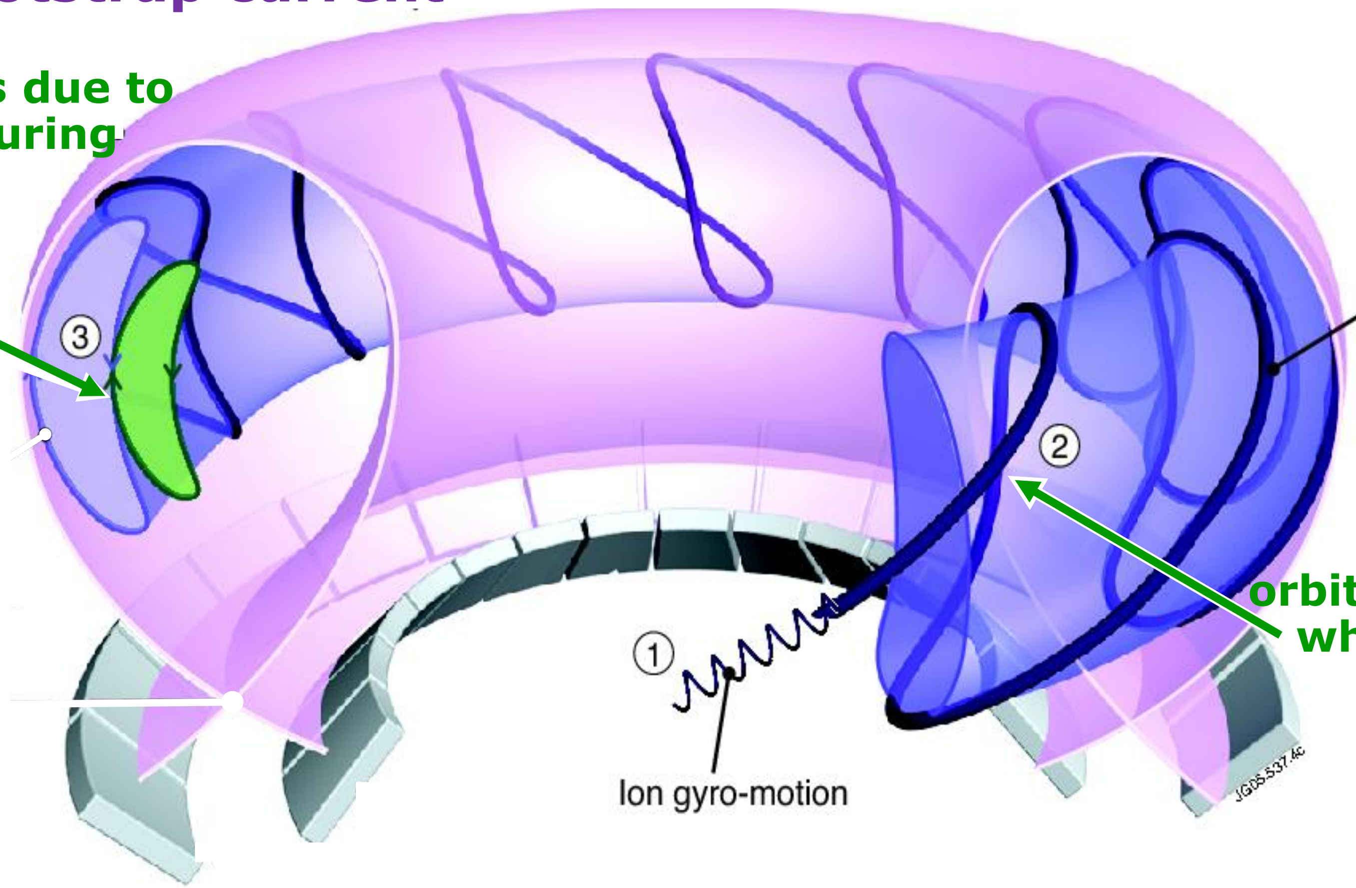
- **Bootstrap current**



http://tfy.tkk.fi/fusion/research/

Current drive and current profile control

- **Bootstrap current**

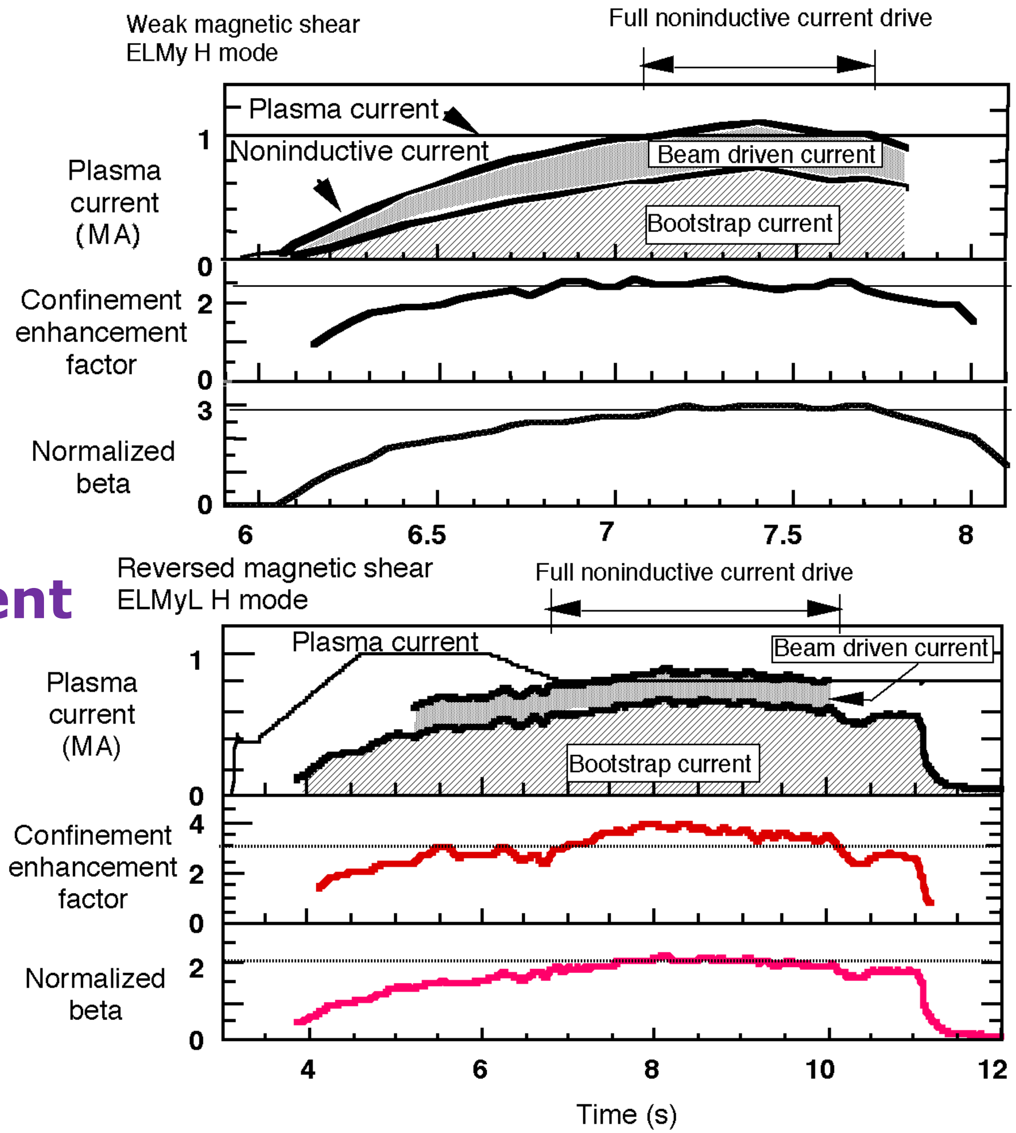


- But more & faster particles on orbits nearer the core (green cf blue) lead to a net “banana current”
- this is transferred to a helical bootstrap current via collisions

$$J_{boot} \sim \frac{dP}{dr}$$

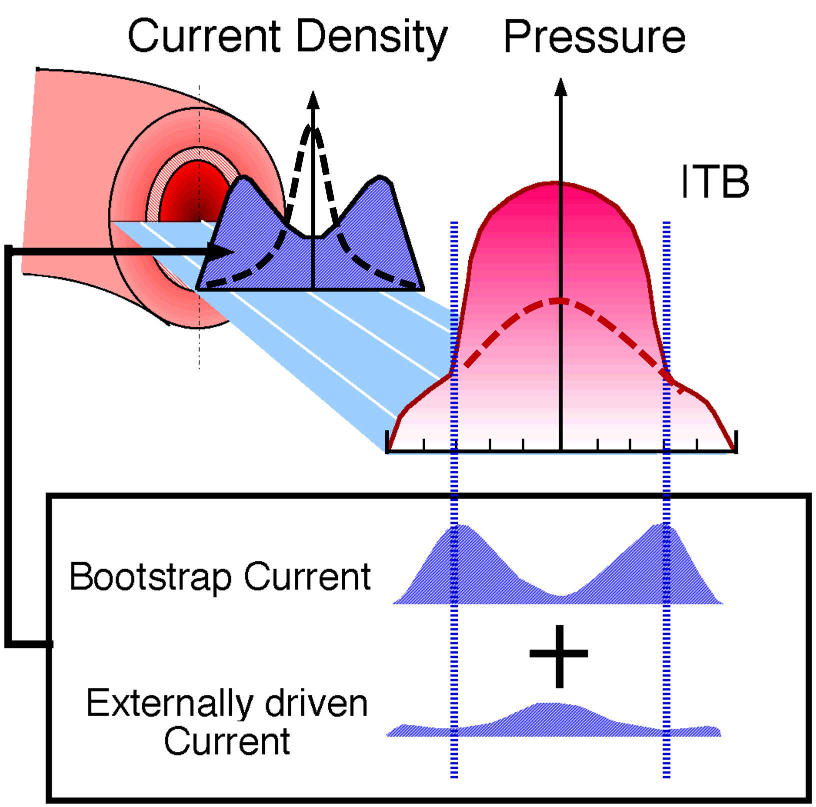
Current drive and current profile control

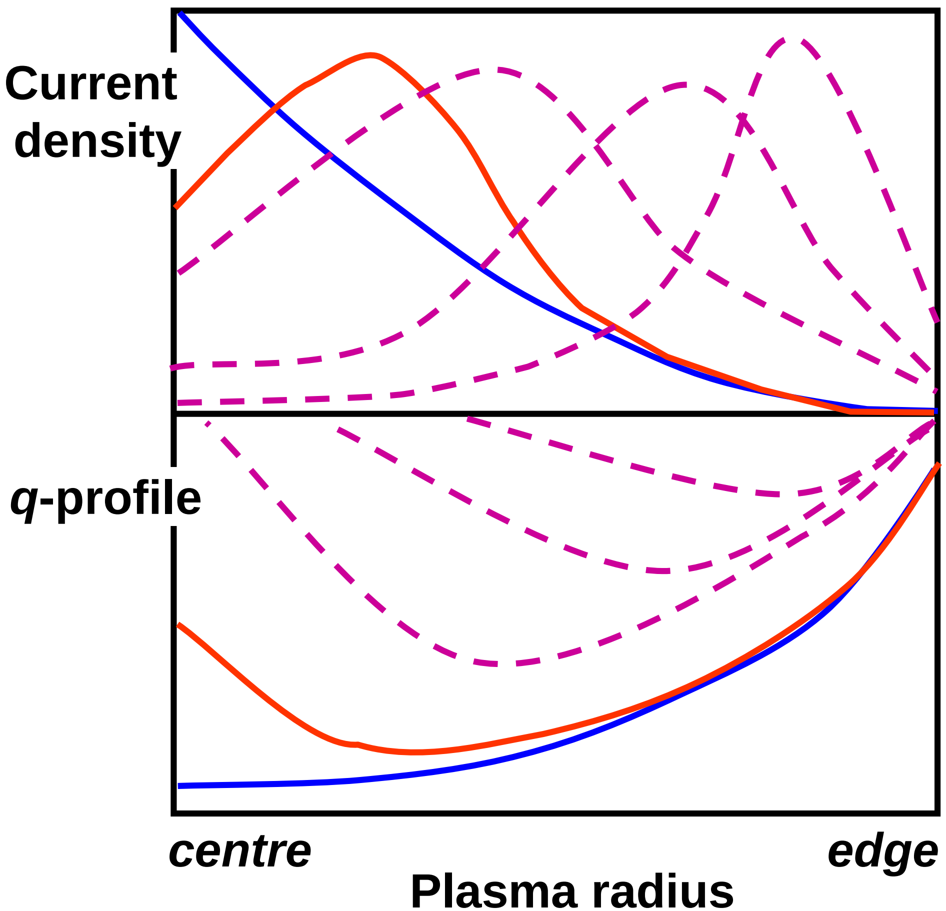
- **Steady state operation utilising the bootstrap current**



Current profile control

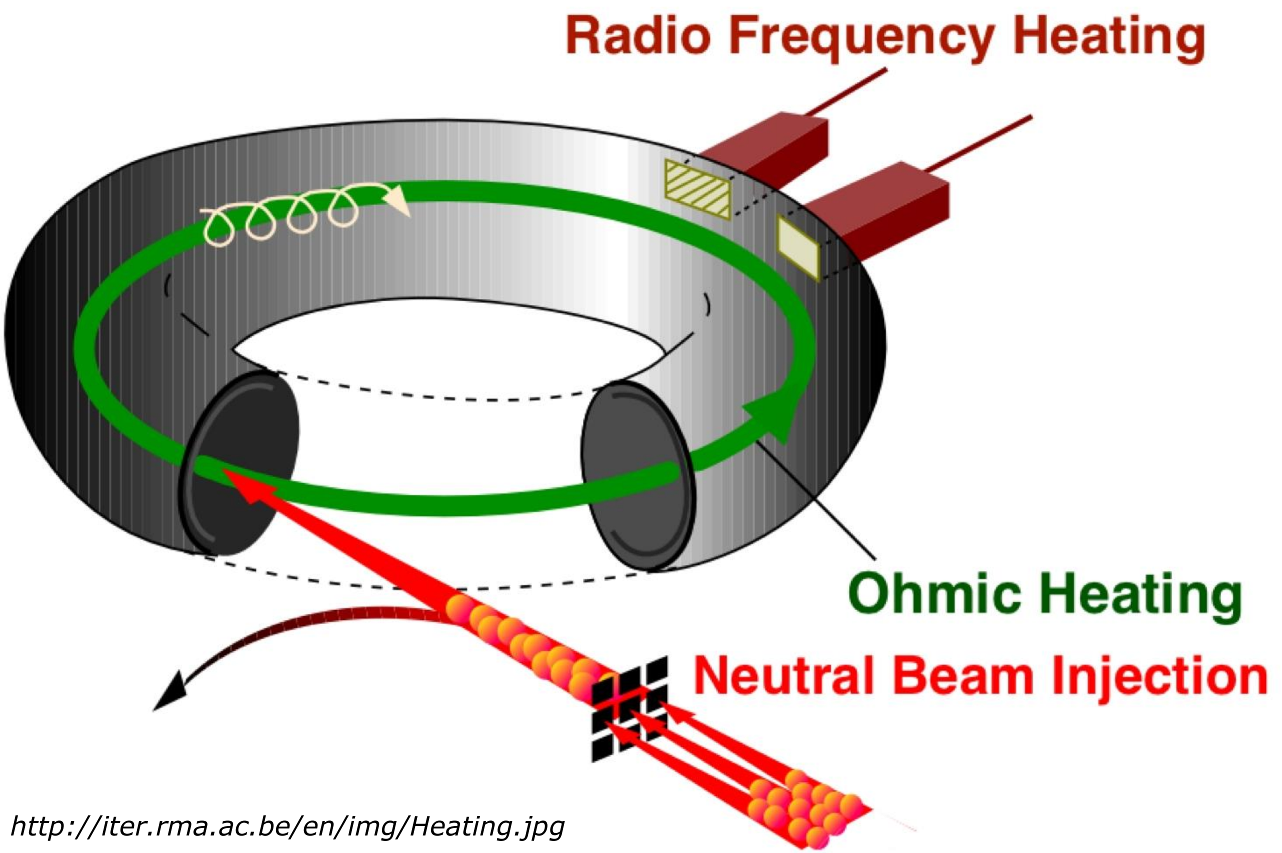
- Plasma current diffusion into the core from the edge





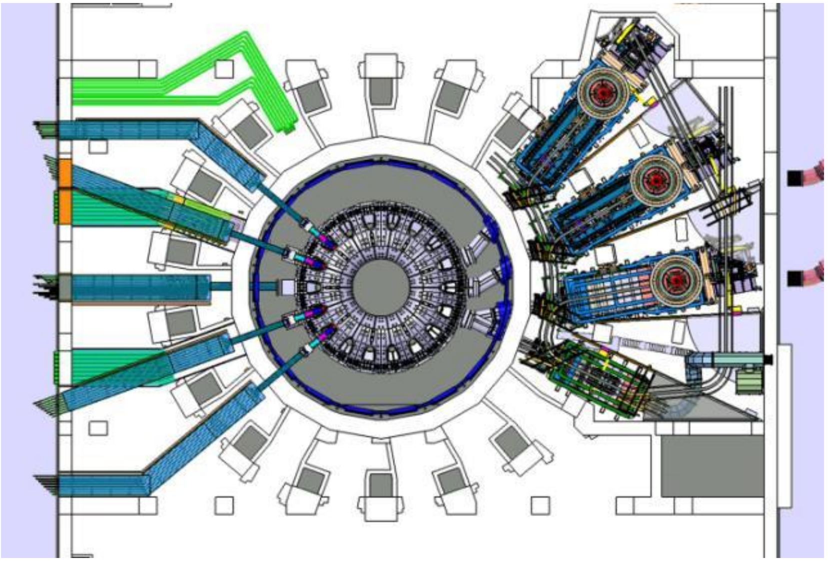
Current and pressure profile control !

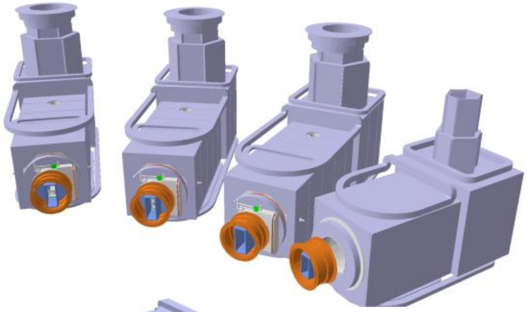
Current drive and current profile control

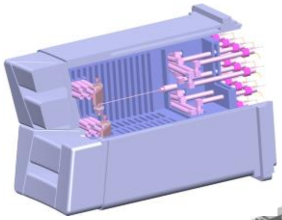


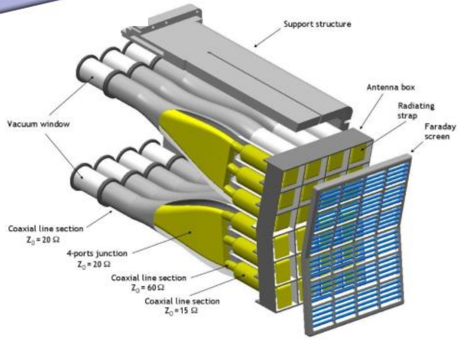
http://iter.rma.ac.be/en/img/Heating.jpg

Current drive and current profile control

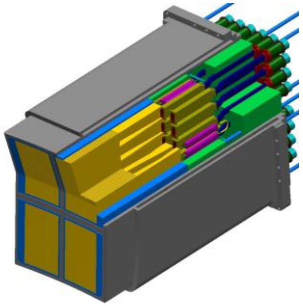








- Heating and CD system in ITER
  - 1 MeV NBI
  - 170 GHz ECRF
  - 40-70 MHz ICRF
  - 5 GHz LHRF



Current drive and current profile control

	Efficiency
LHCD	0.35-0.4
ICCD	0.1xT_e [10keV]
ECCD	< 0.1xT_e [10keV]
NBCD	0.2xT_e [10keV]

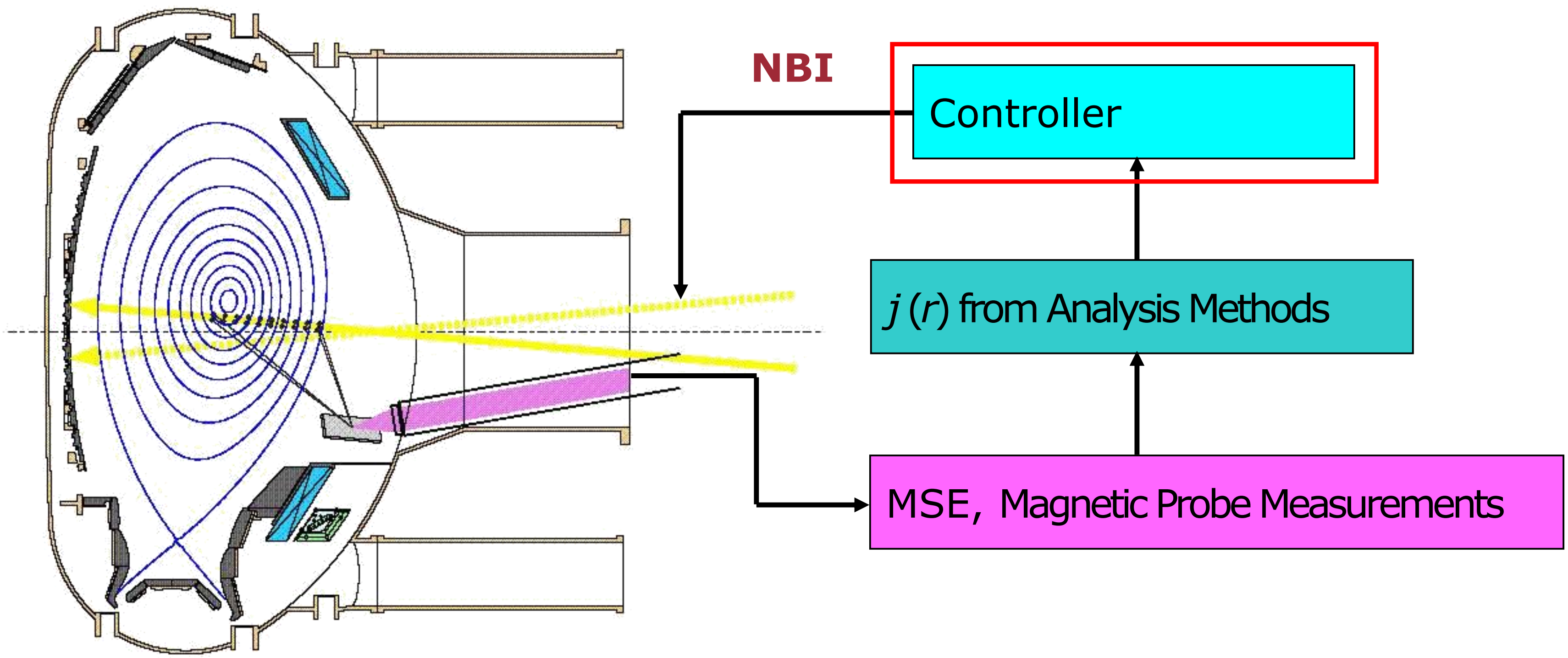
- Efficiency

Theory: $$\eta_{th} = \frac{j}{p} = \frac{e \cdot n_{e\|} \cdot v_{\|}}{\left(n_{ell} \cdot m_e v_{ll}^2 / 2\right) \cdot v_{coll}} \propto \frac{1}{v_{\|} . v_{coll}}$$

Experiment
(Figure of merit): $$\gamma = \frac{n_e\left[10^{20} m^{-3}\right] \cdot R[m] \cdot I[A]}{P[W]} \propto \eta_{th}$$

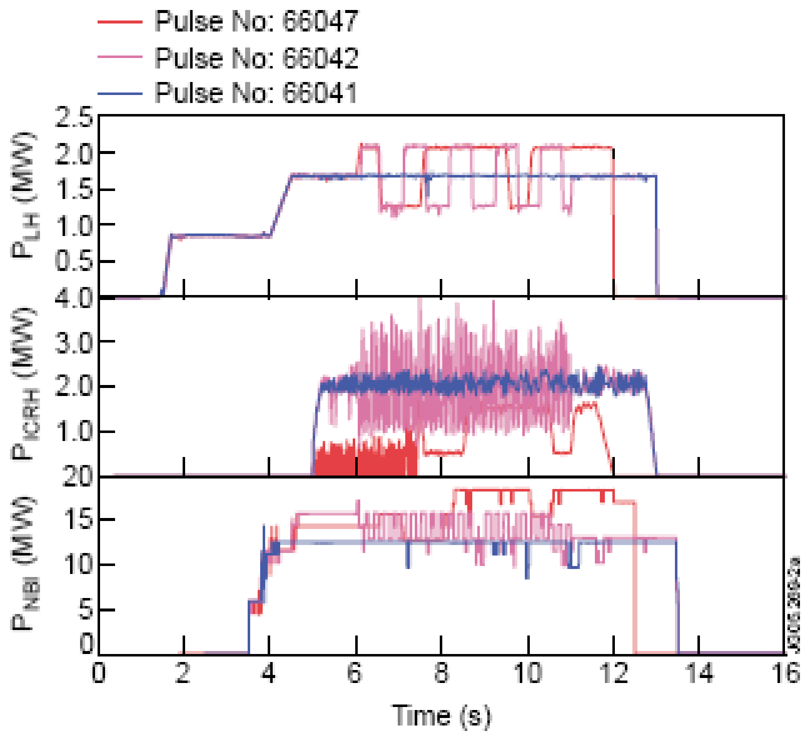
Current profile control

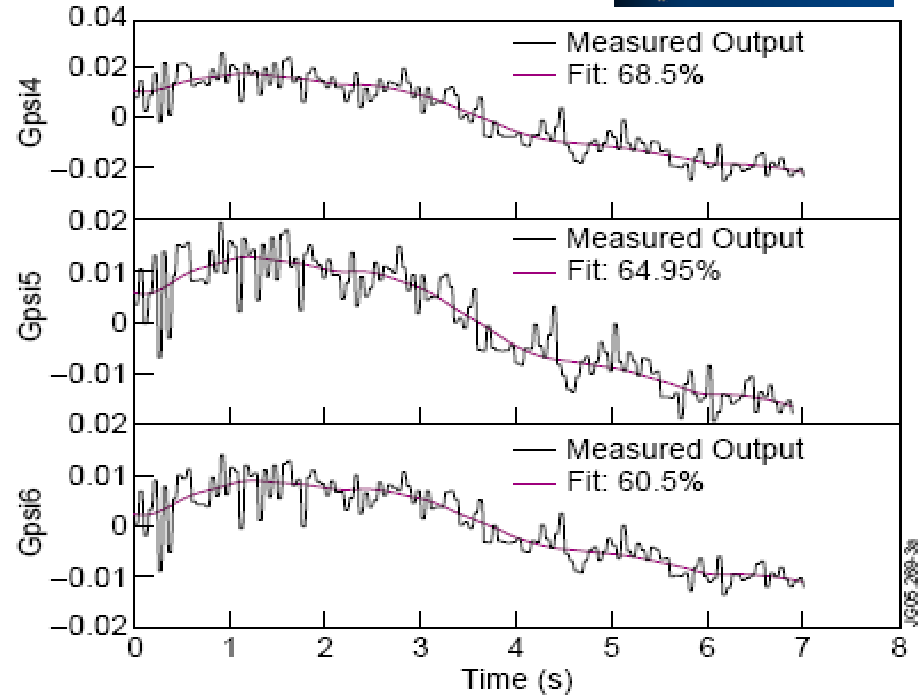
- Current density profile control at ASDEX Upgrade



Current profile control

- Real-time current and pressure profile control at JET

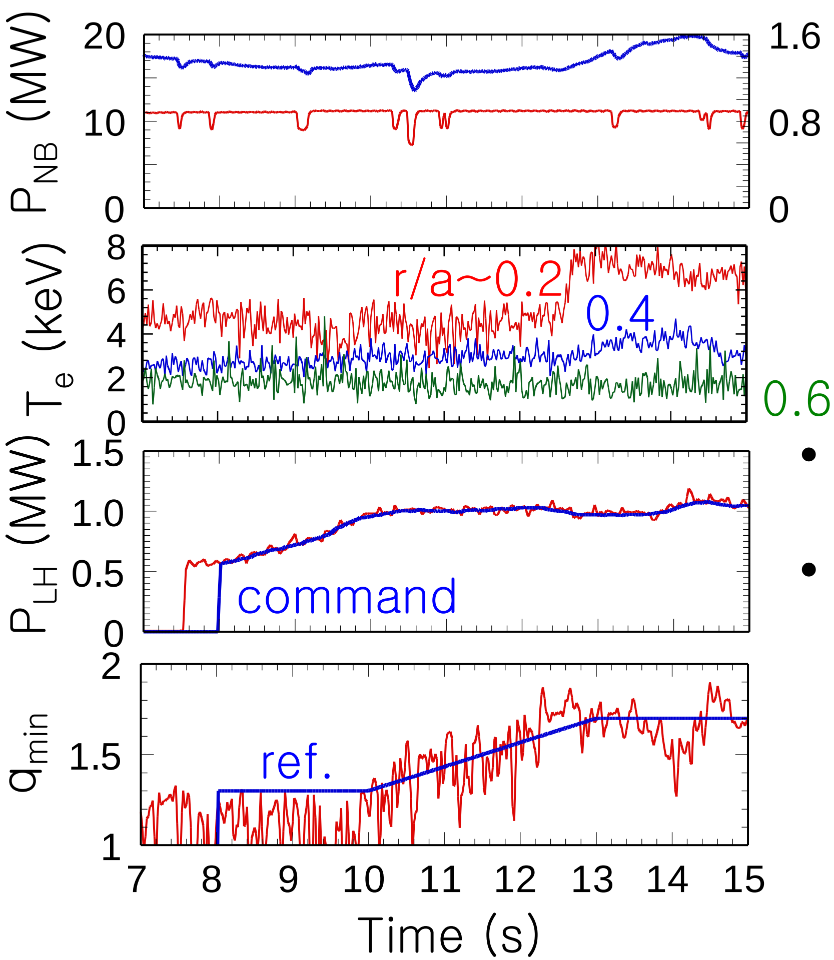




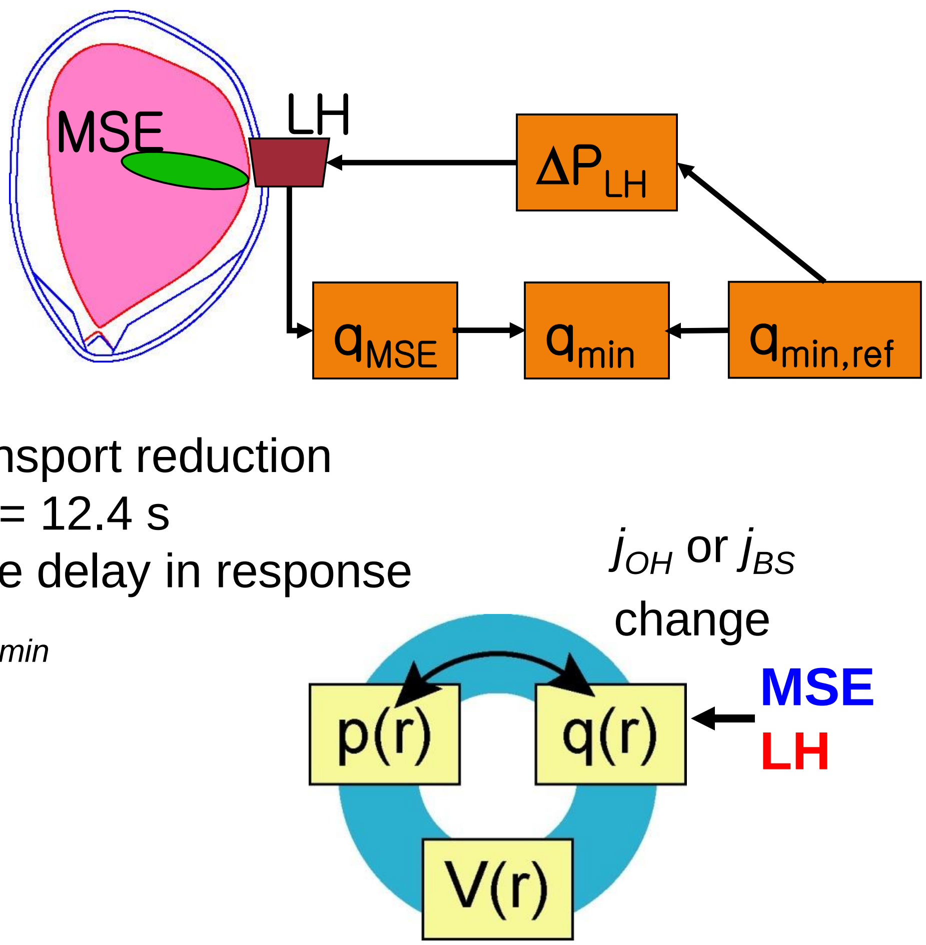
- **Modulation combinations of actuators (NBI, LH, ICRH) to infer the coefficients of the state space model of the slow loop.**
- **Two control loops, 4 actuators (NBI, LH, ICRH, PF)**

Current profile control

- JT60-U: Real time q_{min} control with MSE diagnostics and LHCD

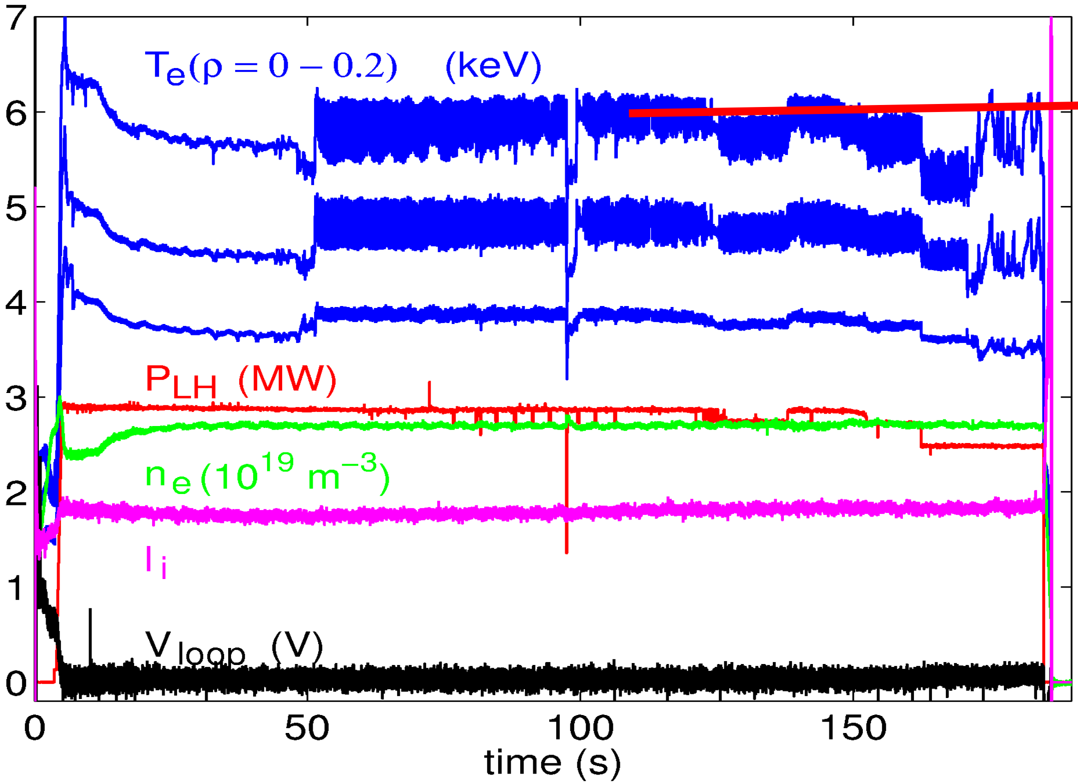


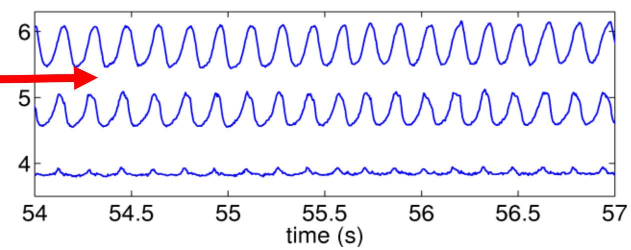
- Transport reduction at t = 12.4 s
- Time delay in response of q_{min}



Unexpected phenomena

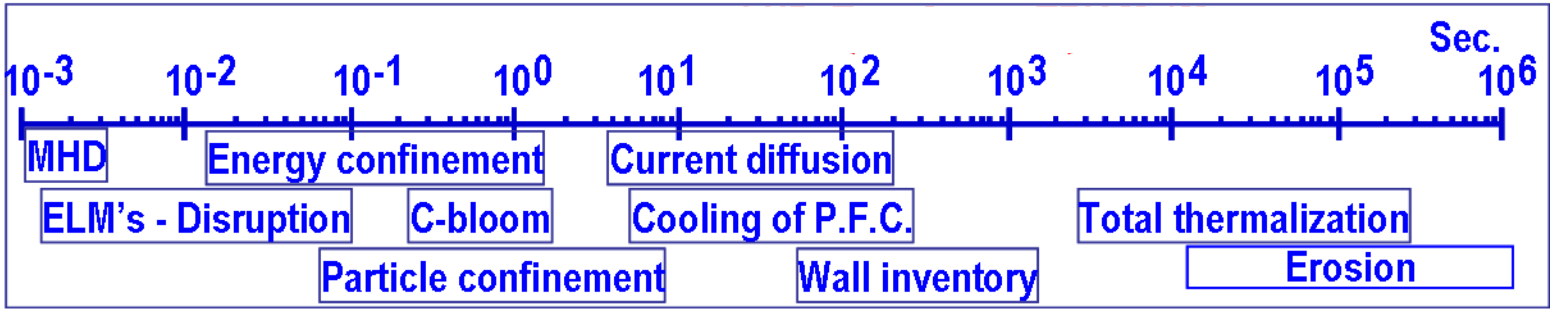
- O-mode in Tore Supra
  - Oscillations of core electron temperature at $V_{loop} \sim 0$
  - Complex coupling between q-profile, MHD (double tearing, e-fishbones), transport and heat sources





Giruzzi, PRL 03, Imbeaux PRL 06, Maget NF 06

Long-pulse operation



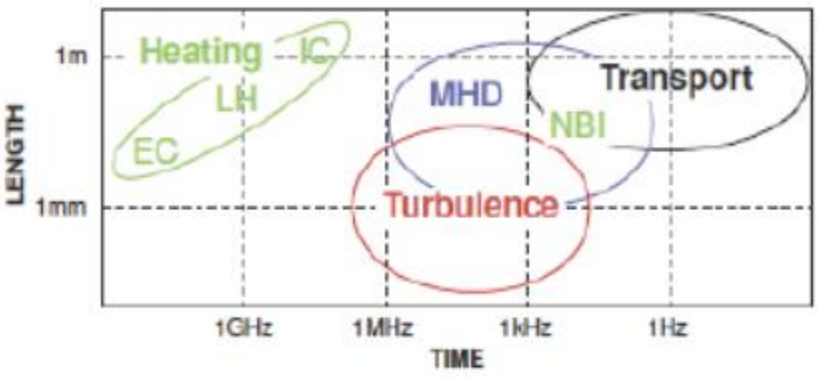
- "Steady-state" refers to a given physics timescale.

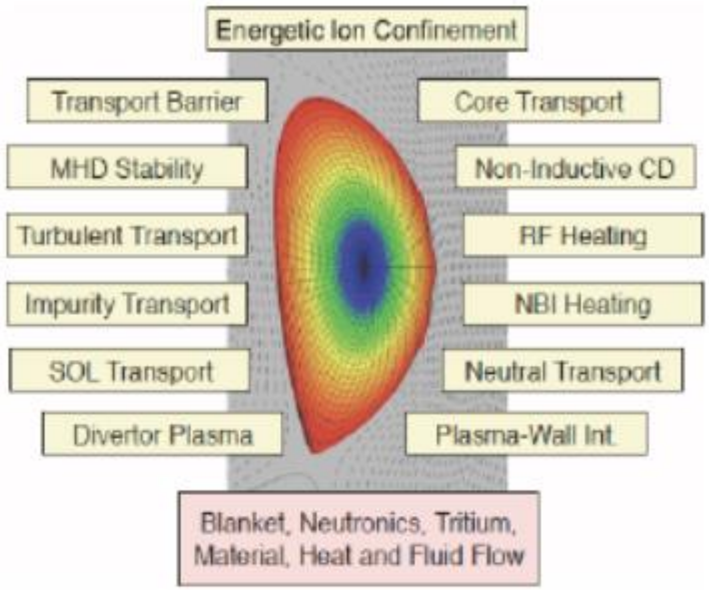
- On present devices, it refers to the Energy confinement time, sometimes to the current diffusion time with fully non-inductive current drive

- "Long Pulse Operation" refers to the integration of physics and technology timescales.

→ **Long Pulse Operation of Fusion Reactors is motivated by a multi-timescale physics problem**

Long-pulse operation

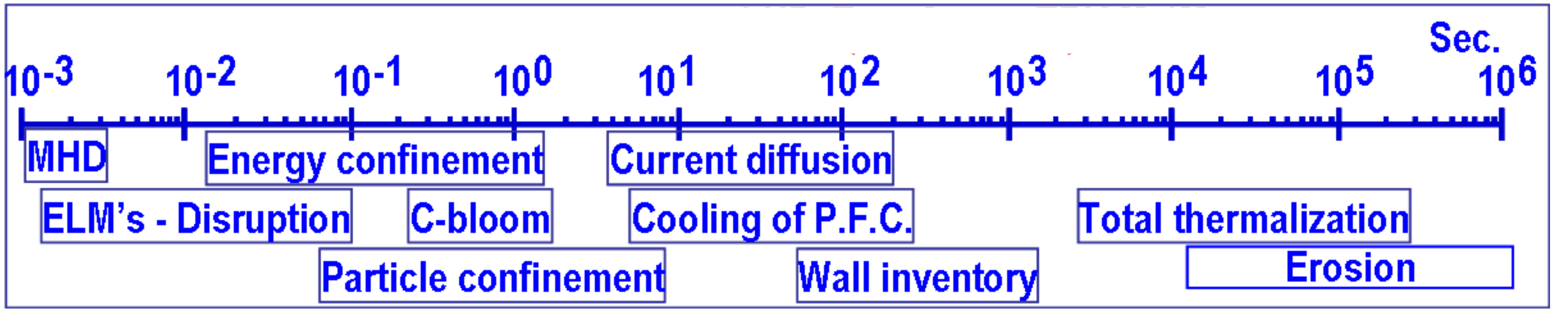




- Time scale 10 ps (100 GHz)~1000 s, spatial scale 10 μm~10 m that includes multi-scale, multi-physics phenomena

A. Fukuyama and M. Yagi, "Burning plasma simulation initiative and its recent progress", J. Plasma Fusion Res. 81 747 (2005)

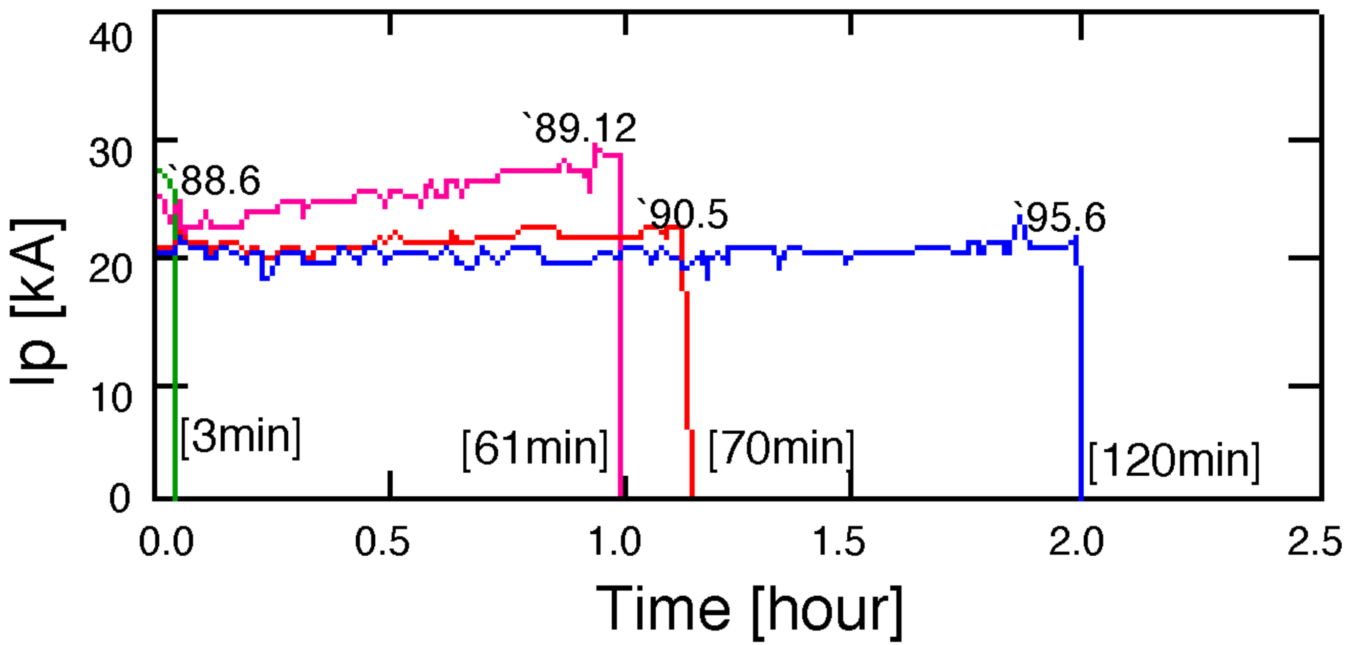
Long-pulse operation



- Long Pulse Operation of Fusion Reactors simultaneously requires

- the long term operation of the magnetic configuration (current profile)
- the long term operation of the kinetic configuration (temperature, confinement, particle content, rotation profiles)
- the long term safe operation of the Coils, Plasma Facing Components, Structure Materials, H&CD systems, Diagnostics, …
- a long term solution for fuel cycle (T)

Long-pulse operation



- The world's longest discharge obtained in TRIAM-1M by means of LH full-CD

Particle exhaust and impurity control

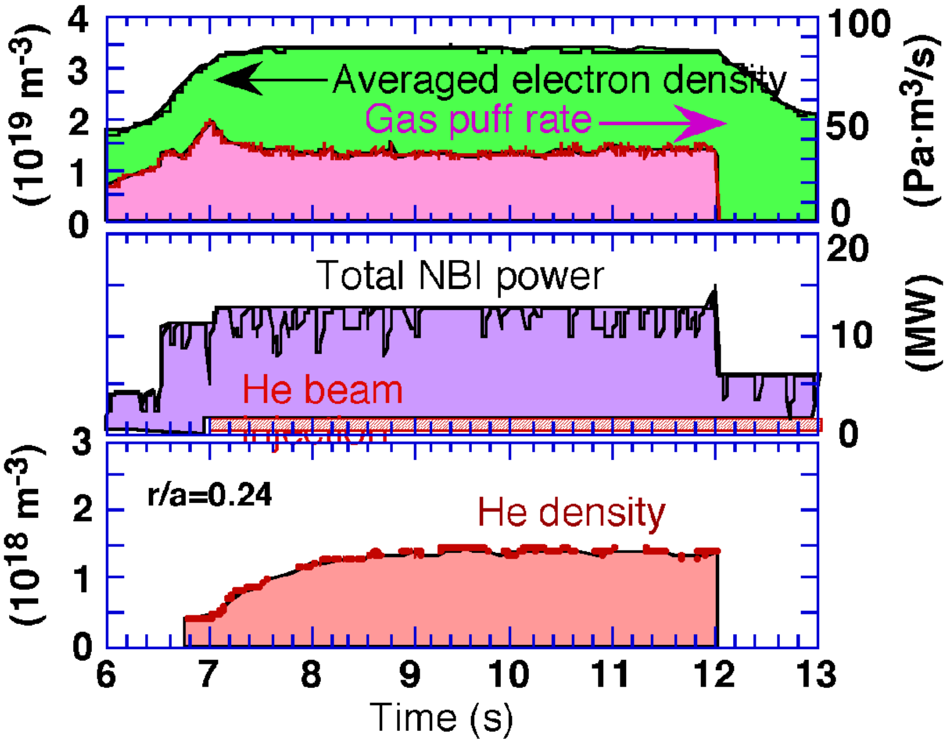
ITER:

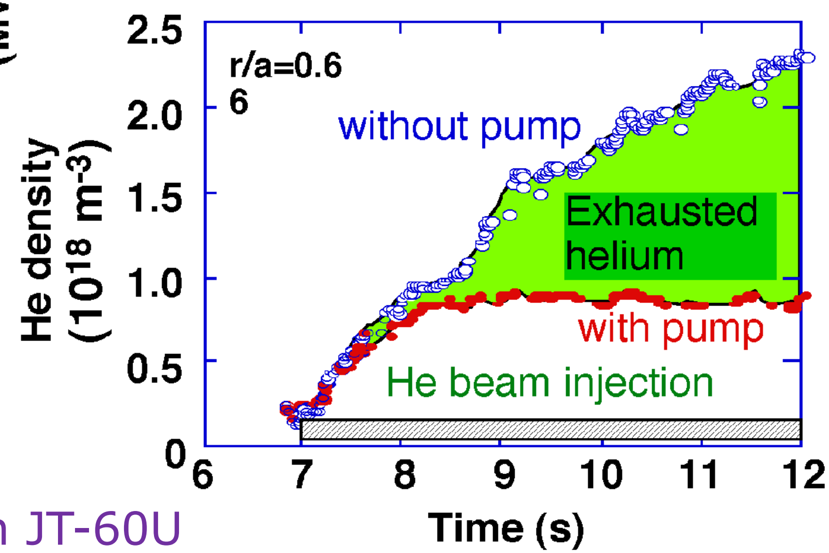
$\tau^*_{He} / \tau_E \leq 5$ Global alpha ptl. confinement time

$Z_{eff} \leq 1.8$

$\eta_{He} = 0.2$ He enrichment factor

$$\eta_{He} = \frac{\left(p_{He} / 2 p_{D_2}\right)_{divertor}}{\left(n_{He} / n_e\right)_{main}}$$

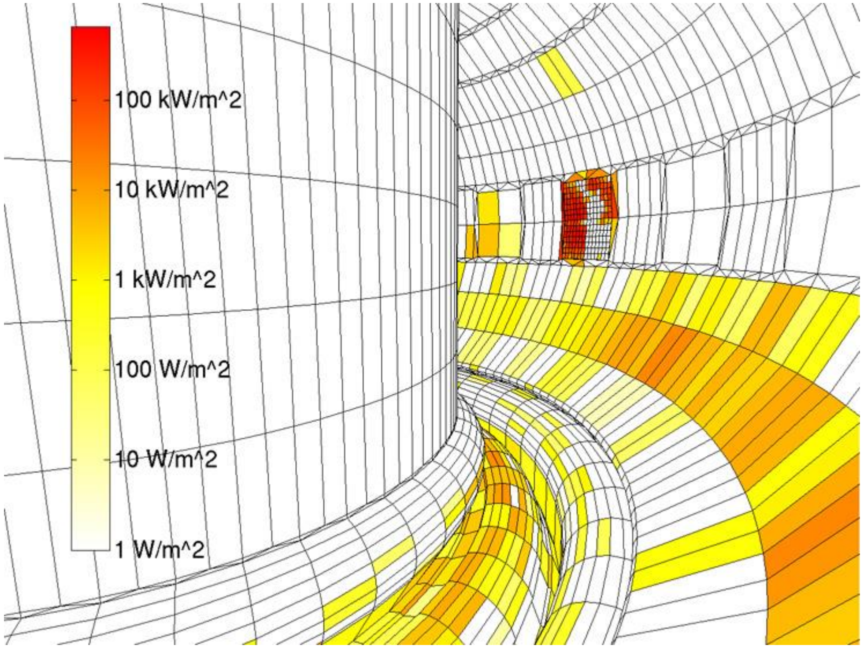




- Simulated He exhaust experiment in JT-60U
  - He beam injected into the plasma
  - Simulating He ash production by the fusion reaction
  - Achievement: $\tau^*_{He} / \tau_E = 4$ $\eta_{He} \sim 1.0$

Divertor heat flux control

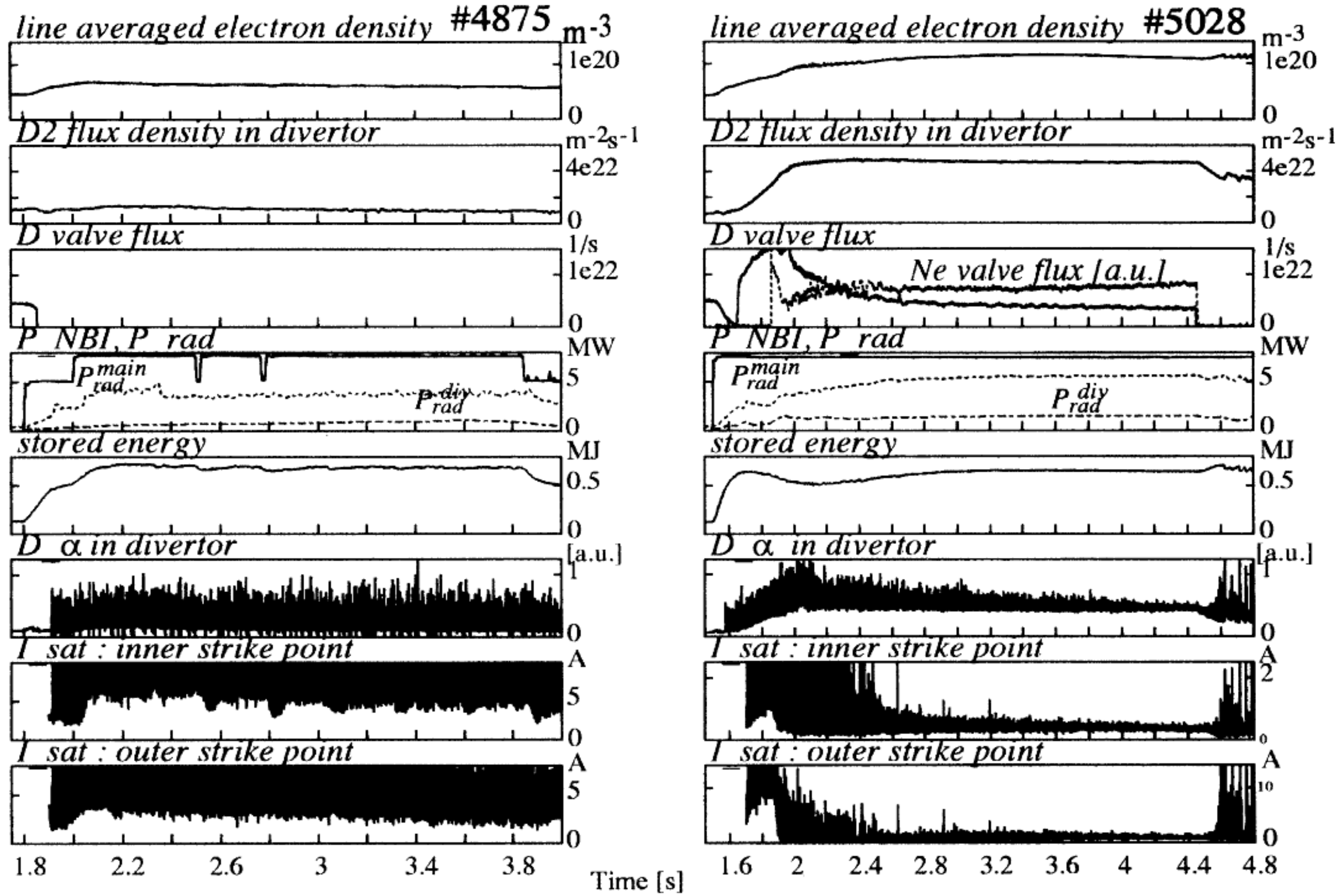
- **Requirements in ITER**
  - High main plasma density of 80-110% of n_{GW}
  - Radiative divertor plasma of 80-95% of the input power
  - Improved energy confinement of $H_{89} \sim 2$
  - Low $Z_{eff} \leq 1.8$



The wall power flux carried onto the wall of ITER by alpha particles

http://www.csc.fi/english/csc/news/news/ferritic_inserts

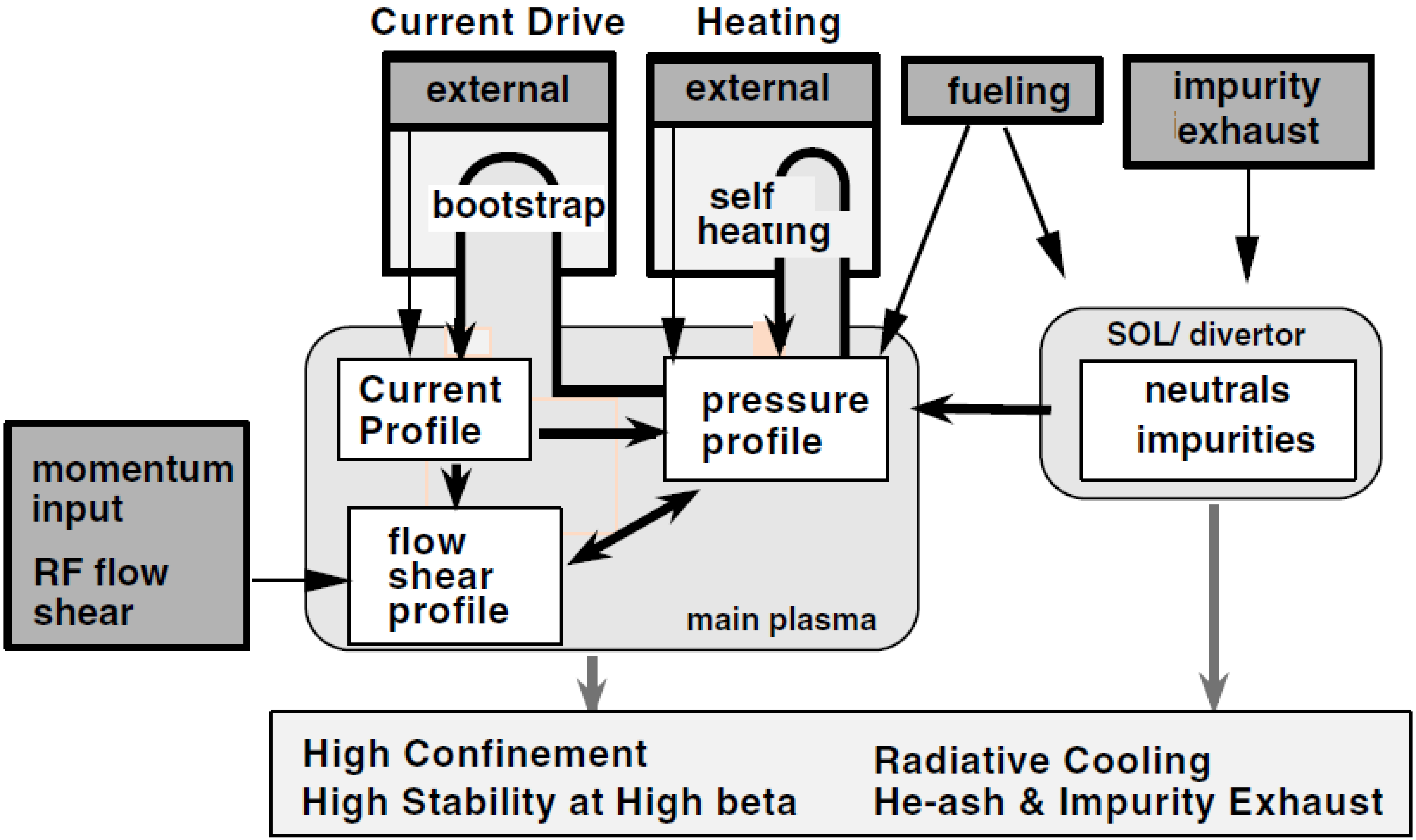
Divertor heat flux control



O. Gruber et al, Phy. Rev. Lett. ***74*** *4217 (1995)*

- CDH-mode in ASDEX Upgrade
  - Total radiation fraction of nearly 0.95
  - Decreased H_{89} slightly from 1.7 to 1.6 due to the increased density
  - Maximum Z_{eff} of about 2.5

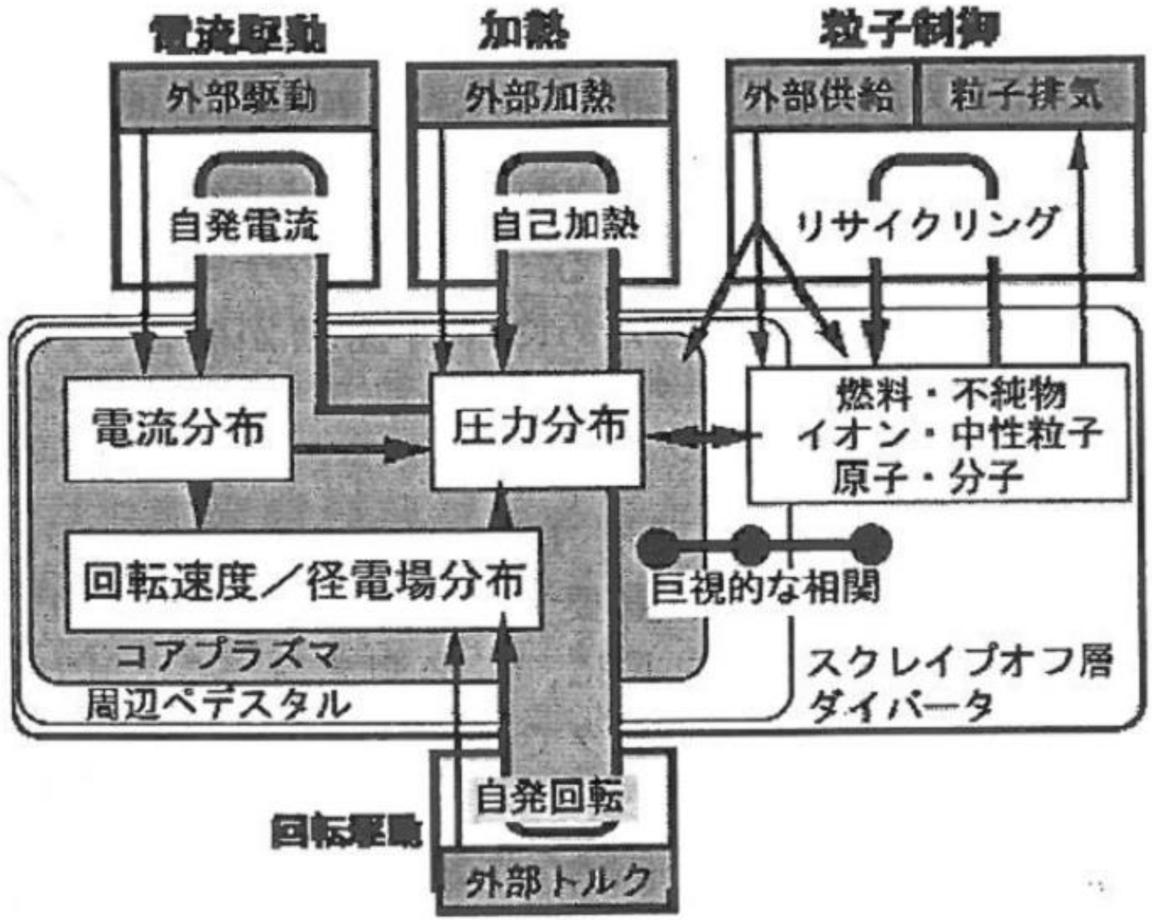
parameter linkage and external controllers for the steady-state tokamak reactor plasma



All profiles have to be optimized as a set.

Y. Kamada, PPCF ***42*** *A65 (2000)*

parameter linkage and external controllers for the steady-state tokamak reactor plasma



*Y. Kamada, PPCF **42** A65 (2000)*