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Steady-State Operation of "Advanced Tokamak" regimes.

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with the help of the JET ***Task Force B***

Outline

- **Introduction**
- **Some “AT” results on Tore Supra and JET**
- **Requirements and on-going actions, focusing on steady-state operation aspects**:
  - scenario
  - NICD
  - Ti <-> Te
  - MHD
  - feedback
  - codes
  - ....
- **Conclusions**

The DRFC/SCCP now works for both ***Tore Supra*** *and* ***JET*** *"AT" physics*

- program:

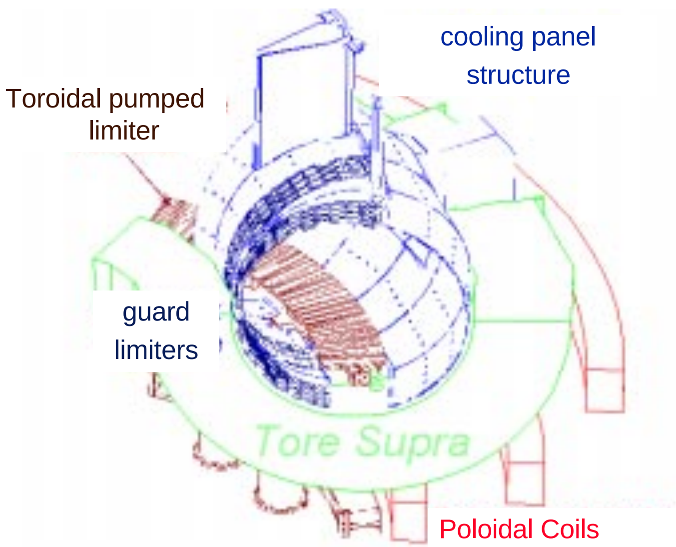
high power-long pulse operation

- tools

ICRF + LHCD + (ECRF)

super conducting TF-coils

upgraded inner-vessel (FY00, CIEL)



- program:

performances, DT plasmas

- tools

NBI + ICRF + LHCD

- Extension of JET,

  FY 00->02

- MACHINE OPERATED BY UKAEA
- ACTIVE PARTICIPATION OF EURATOM ASSOCIATIONS TO THE JET EXPERIMENTS.
- DRFC/SCCP INVOLVED IN "AT" PHYSICS, FOCUSING ON STEADY-STATE ASPECTS (up to 10-15 pmy).

mid-term "AT" topics

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- RF-driven AT physics
- Vloop=0: LHCD+bootstrap
- current diffusion
- current profile control
- long-term MHD stability
- fast particle (e-, ion) physics
- edge physics:
  - wall-plasma equilibrium
  - RF-edge physics
- particle fuelling
  - multi-pellet injection

JET

- ->31/12/99 Task Force B

  (see JET presentation)
- FY 00->02

  to be discussed:

  ITBs, D-T plasmas,

  α-particles, ...

Tentative characterisation of an "Advanced Tokamak" discharge

- **Enhanced confinement**,

  (in particular with respect to the simple Ip-scaling)
- **through active profile modification & control**,

  (j, ExB, n, plasma shape, ...)
- **for steady-state tokamak operation**.

  (fully non-inductive current drive)

  (controlled edge physics)

Confinement enhancement due to current profile shaping on TORE SUPRA

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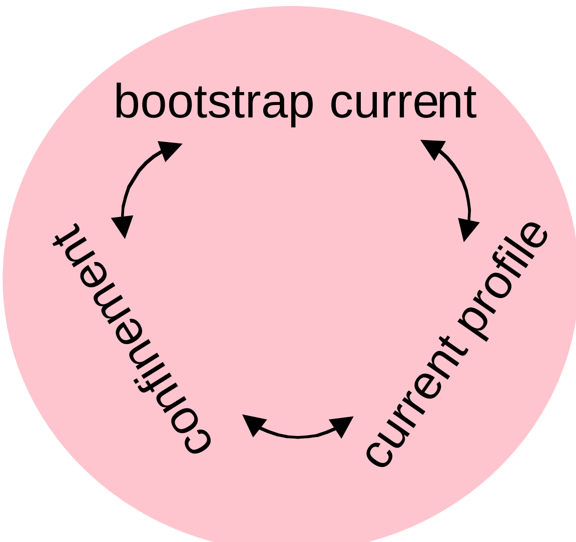
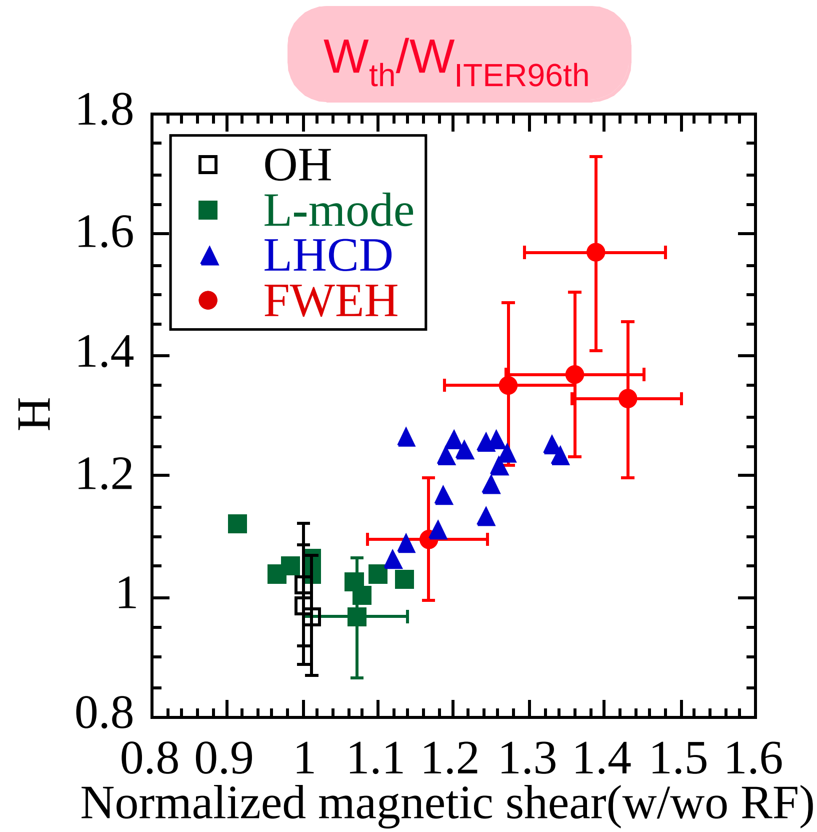
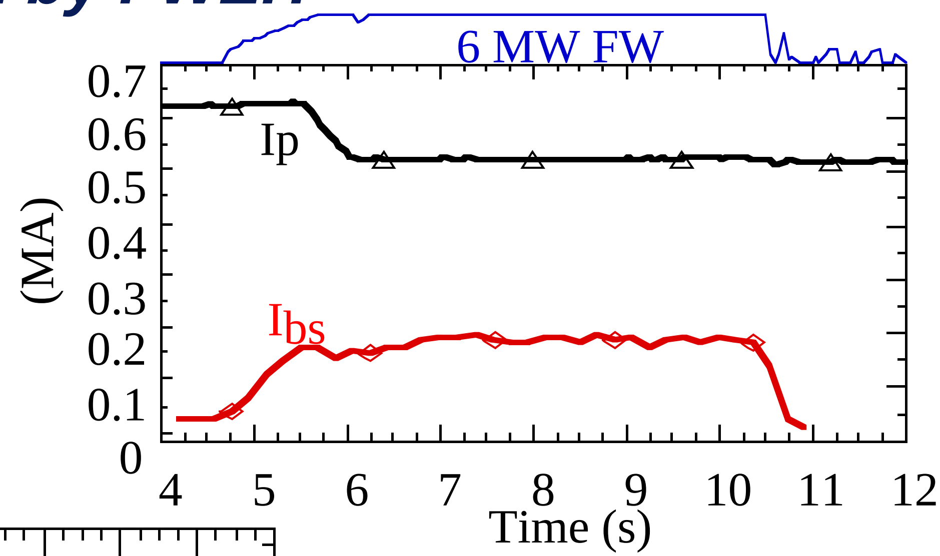


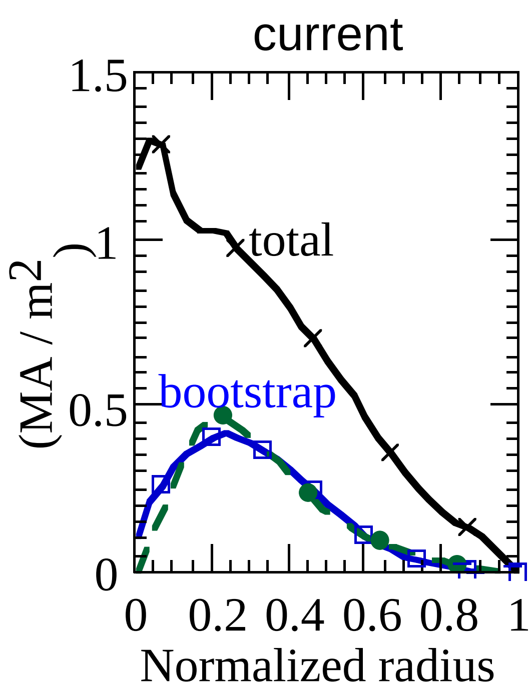


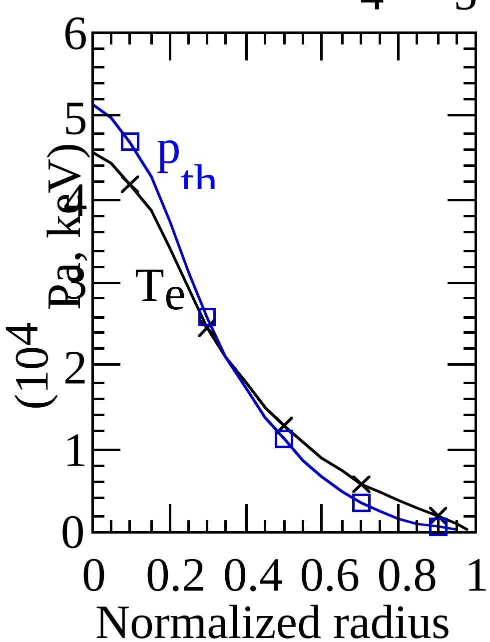
Bootstrap current driven by FWEH

$P_{FW} = 6MW - 5s$

$I_{bs}/I_p = 35\ \%$







#18805

modif. crt profile:
Te barrier sustained by LHCD on Tore Supra

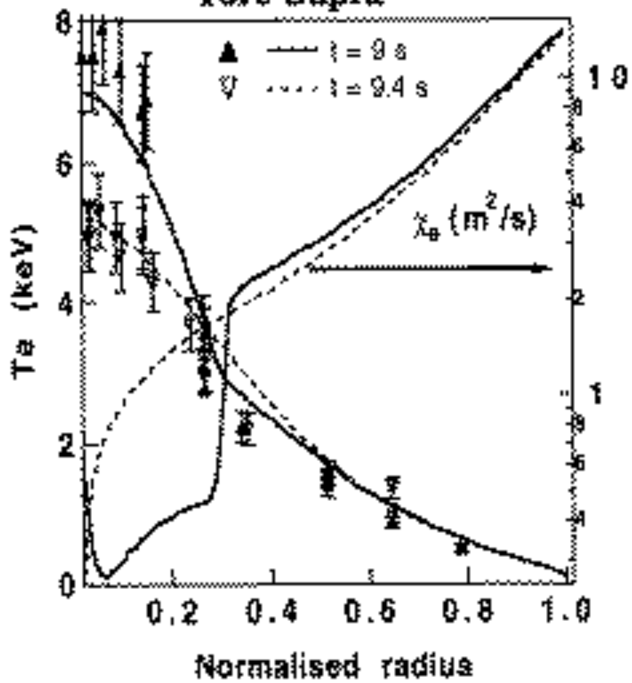
modif rotation shear
Record Tio = 40 keV in DT on JET

ITB formation and expansion (H(Rfoot-Ti))

Electron ITB in DD and DT

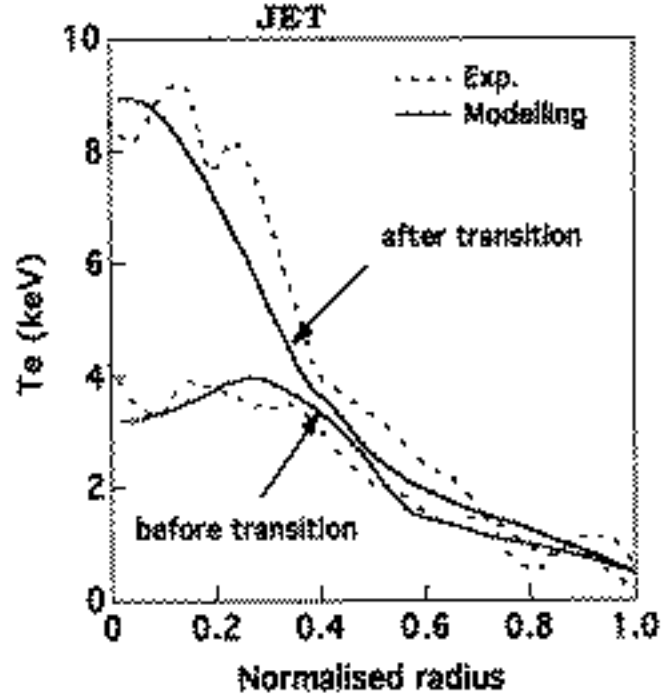
T_e barrier sustained by LHCD and transport modelling

Tore Supra



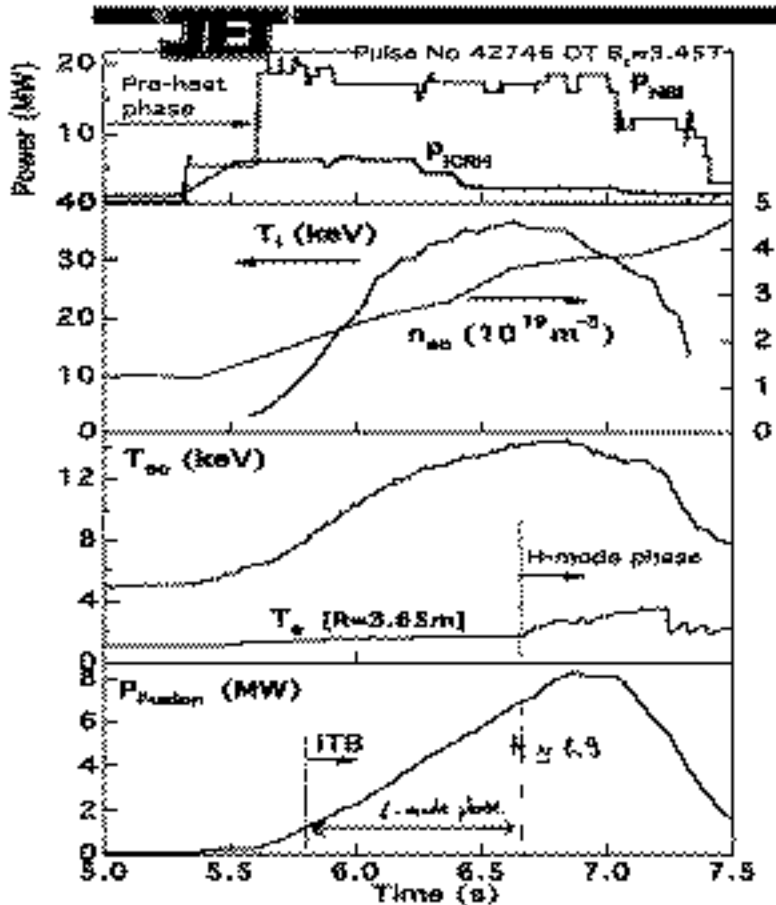
Litaudon 1997, 12th Top. Conf. on RF power in plasmas, Savannah 137.

JET



Ekedahl 1997, 12th Top. Conf. on RF power in plasmas, Savannah 169.

12th Top. Conf. on RF Heating, Brussels, 20-23 January 1998 Xavier Litaudon 10



2. ITB with dominant ion heating schemes

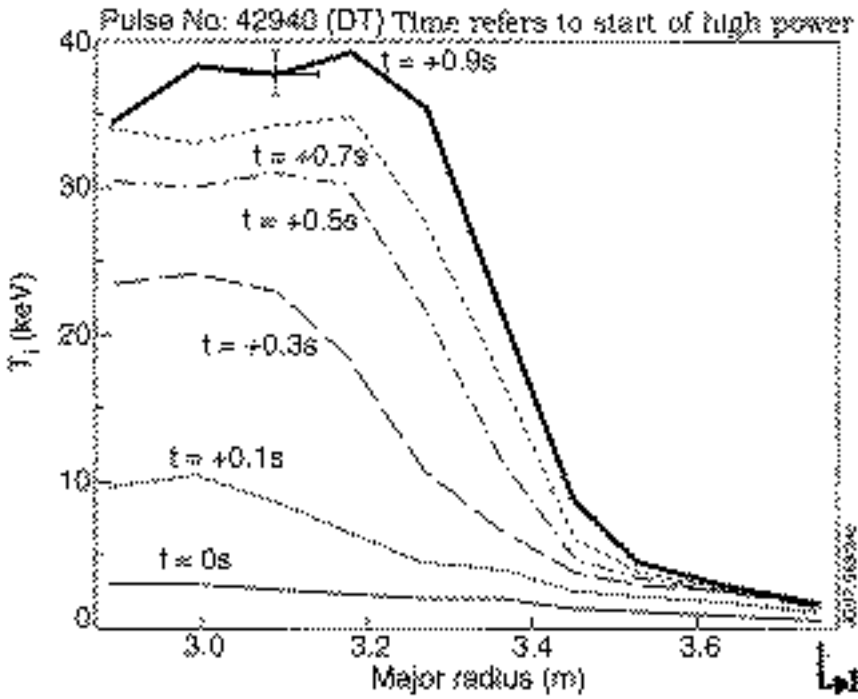
- Preheat phase with LHCD & ICRH during ramp-up phase
- **First successful production of fusion power, 8.2MW, with ITB in D-T plasmas**
- **ITB in D-T with similar power levels to D-D**
- T concentration ≈ 30%
- B_0 = 3.45T/I_p = 3.2MA

C. Gormezano et al 1998, Phys. Rev. Lett. 80 5544

Prague, June 29-July 3, 1998 Xavier Litaudon

JET

Record $T_{io} \approx 40$ keV in D-T at higher B_o



- ITB expansion
- $n_{eo} \approx 4x10^{19}\ m^{-3}$
- $\nabla T_i \approx 150 keV/m$
- $\nabla p_i \approx 10^6 Pa/m$
- $f_{rot} \approx 37kHz$
- $n_{io} T_{io} \tau_E \approx 10^{21}\ m^{-3}$ keV s

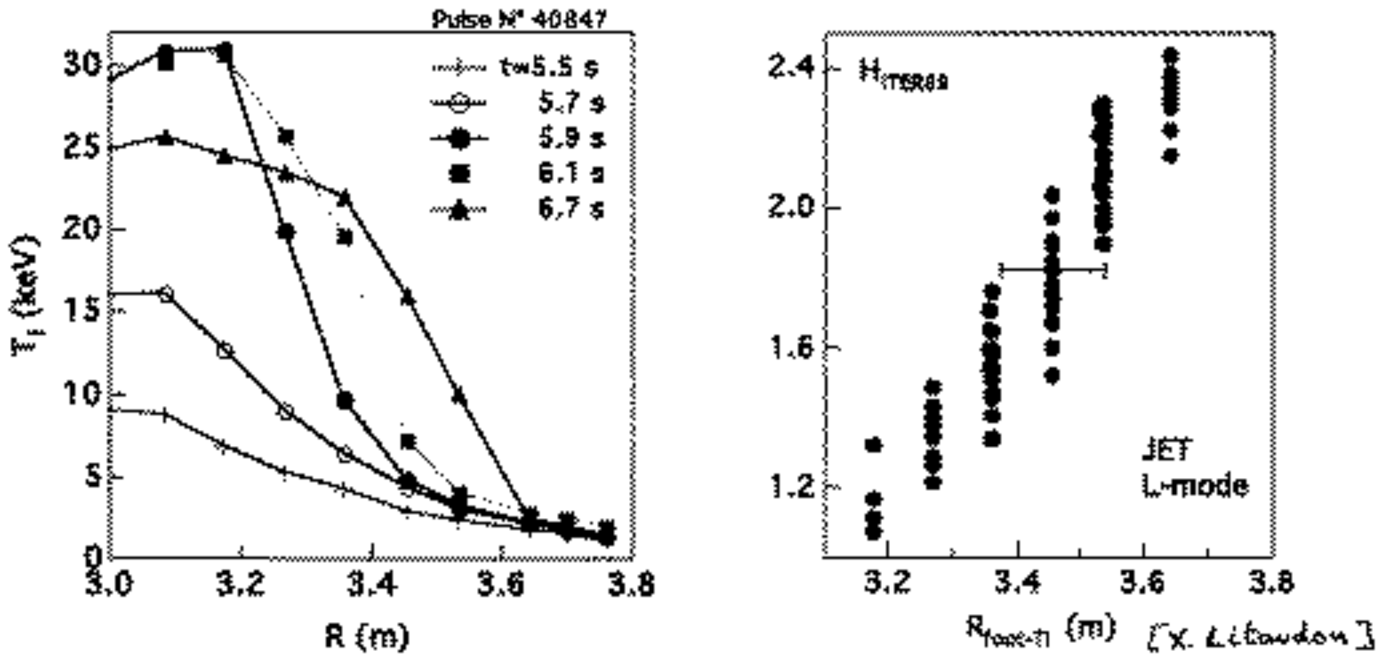
$B_o \approx 3.85T/I_p \approx 3.4MA$

Plasma edge : R~3.9m

...gue, June 29-July 3,1998 Xavier Litaudon

Internal transport barrier formation and expansion

JET

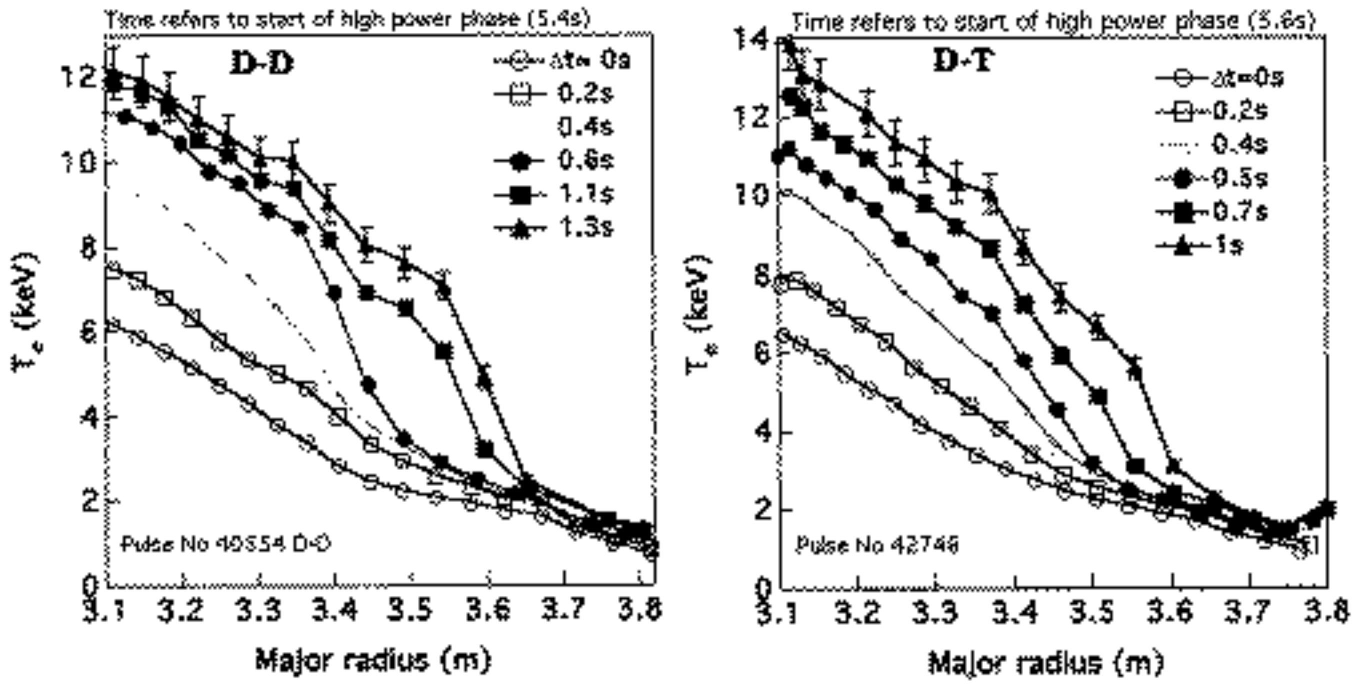


JET team (presented by F. Söldner) 1997, 24th EPS conf., Berchtesgaden.

JET

Electron ITB in D-D and D-T

Te-profiles : ECE Heterodyne Radiometer



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Thermal transport in advanced tokamak scenarios: ITB formation modeling.

- $\chi = \chi_{Bohm} F(s_m, \gamma_E) + \chi_{gyro\text{-}Bohm} + \chi_{neo}$
- **Magnetic (s_m) and ExB (γ_E) shear correction**

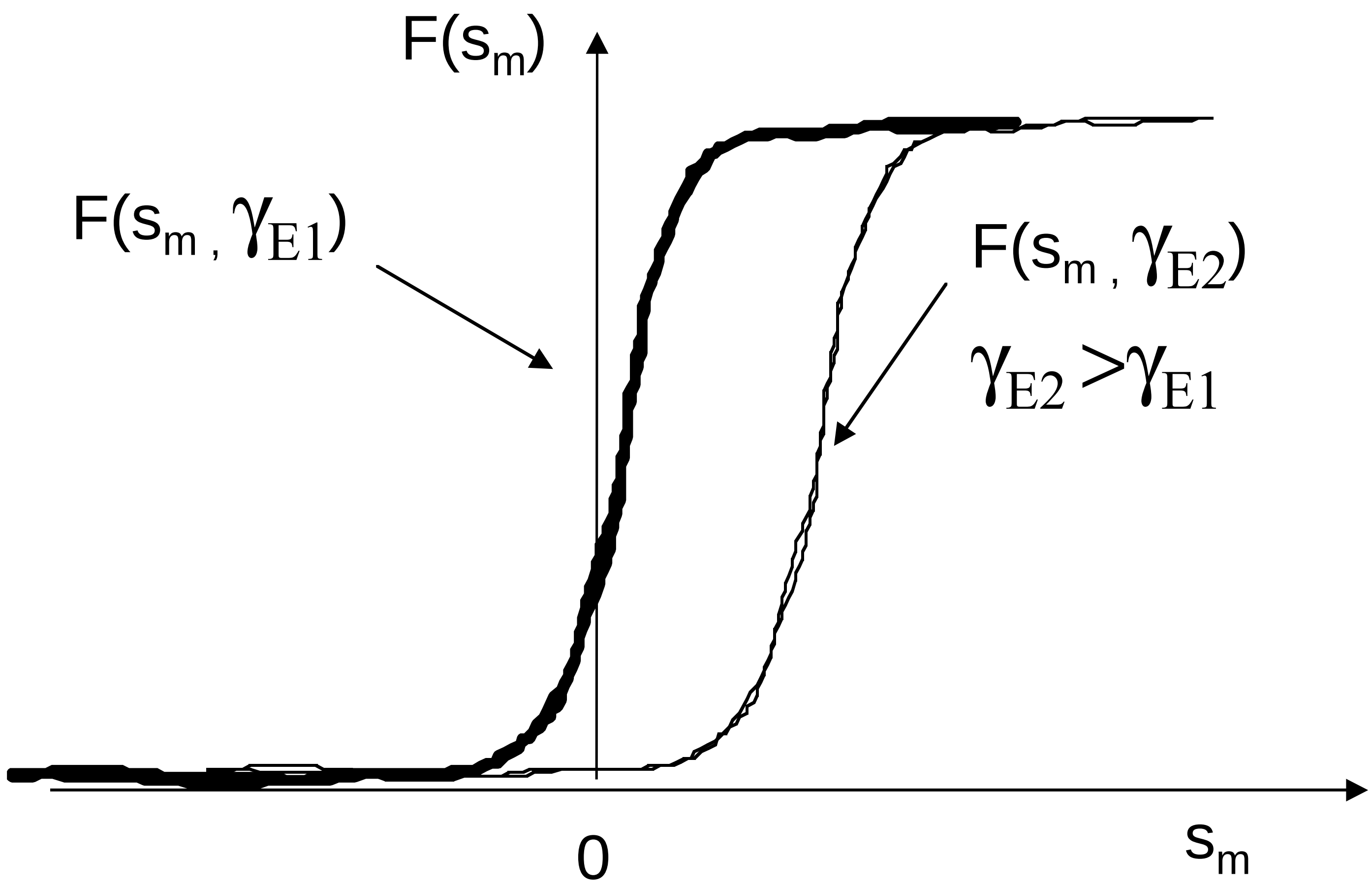
$$F(s_m, \gamma_E) \approx \exp(-(s_{cr} - s_m))$$

- **Turbulence stabilization when** $s_m \ll s_{cr}$

critical shear $s_{cr} \propto 0.05\ \mathrm{abs}(1 - \gamma_E / \gamma_{lin,max})$

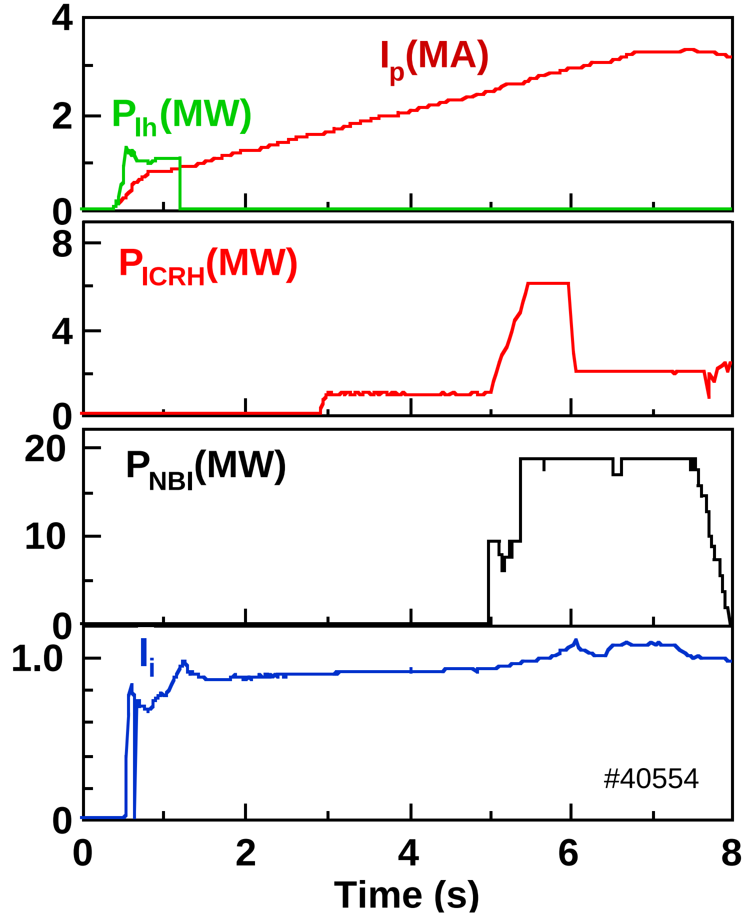
Parail V. et al Nucl. Fusion 1999
Voitsekhovitch I. et al., IAEA, 1998

$F(s_m, \gamma_E)$ *versus* s_m *for various* γ_E



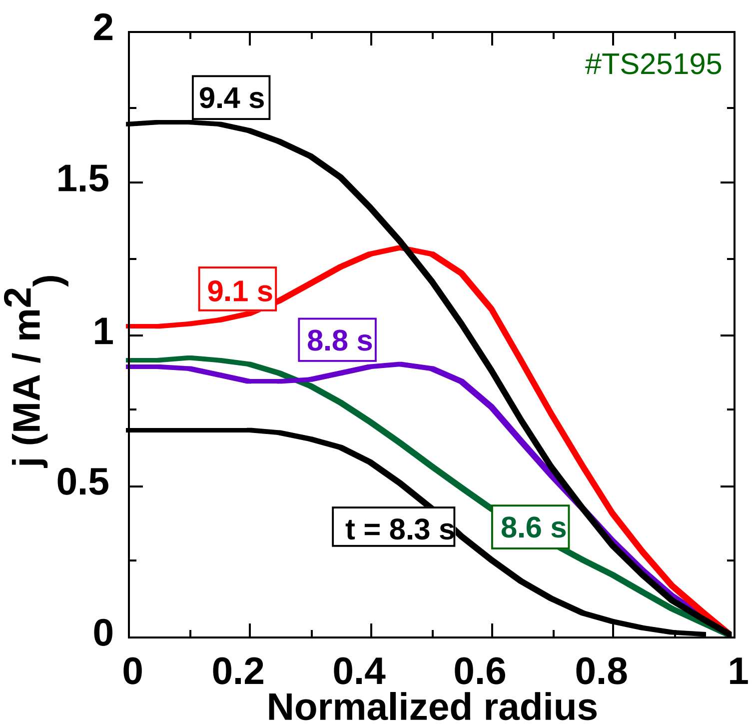
Current ramp-up scenario on JET

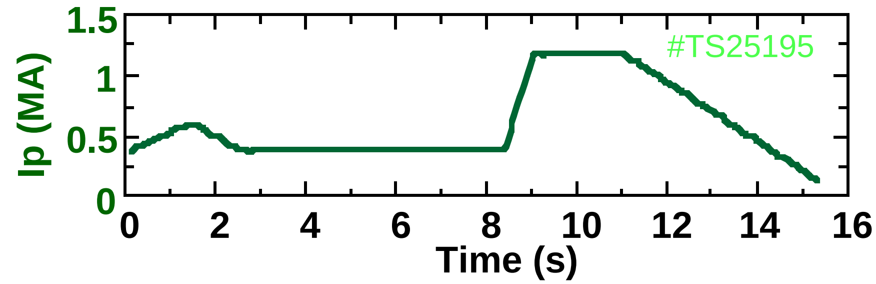
Gormezano 1997, 12th Top. Conf. on RF power in plasmas, Savannah p3.

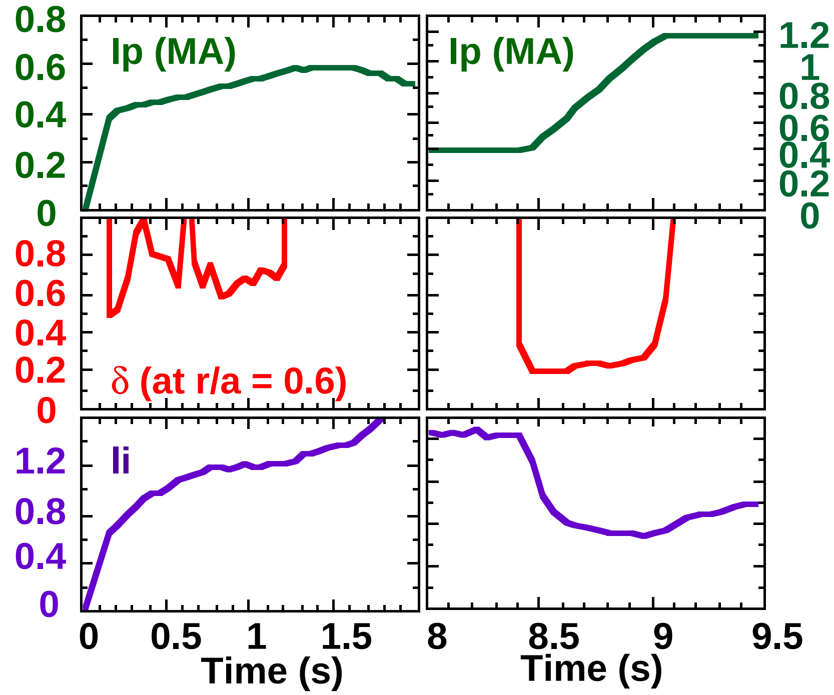


Current ramp-up scenario on TORE SUPRA

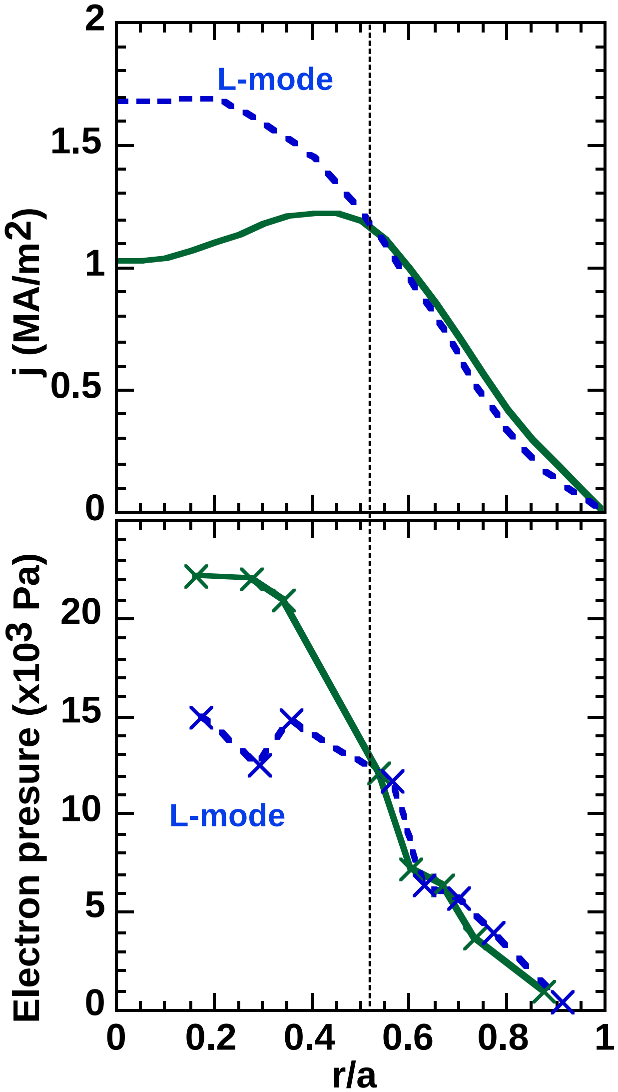
- current ramp-up
- on-axis electron heating

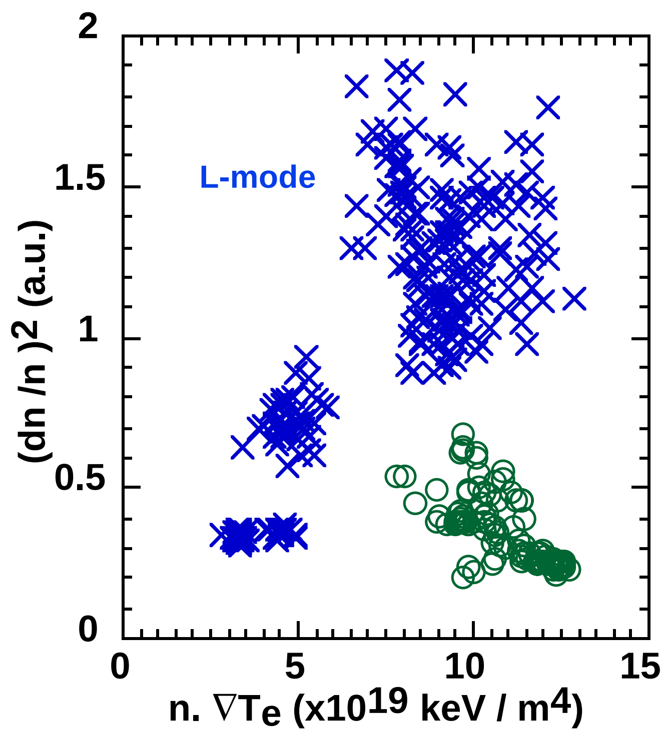






turbulence (CO_2 laser scattering)





Fluctuations (k = 8 cm^{-1})

cf G.T. Hoang et al, 13th Top. RF Conf., Annapolis

current ramp-up: discussion

- Current ramp-up is in fact used as an off-axis CD method
- The regimes obtained are "frozen" on time-scales smaller than the current diffusion time.

*

-> necessity to use NICD methods
to fully drive and control the current profile.
-> necessity to rely on a large bootstrap current fraction
(external current drive methods not efficient enough)
-> role of a current "pre-forming" phase for SS operation
- optimization of the route to steady-state. ⇨
- one or several final states? ⇨

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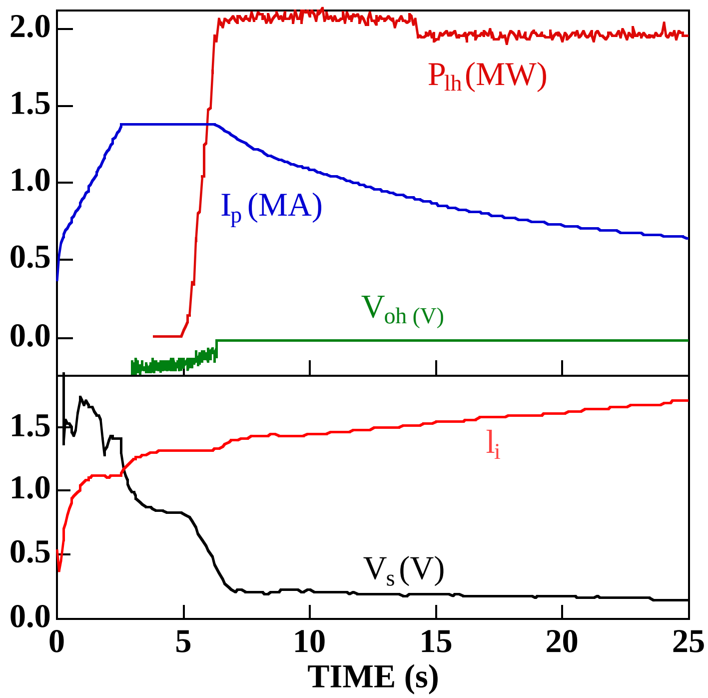
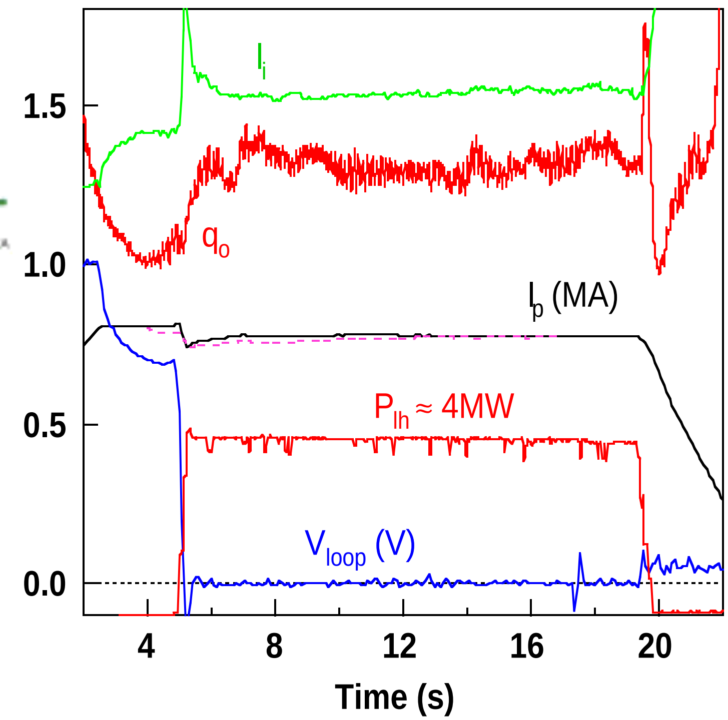
optimization of the route to steady-state

Constant primary voltage operation: Long time scale to reach plasma equilibrium



Magnetic flux feedback control for fully non-inductive operation



$E_{//}(r,t)=0$ for $\Delta t \geq 3$ s

Kazarian F. et al., 1996, PPCF **38** 2113

one or several final states?

- Internal plasma relaxations
- Mechanism
- O-D modeling

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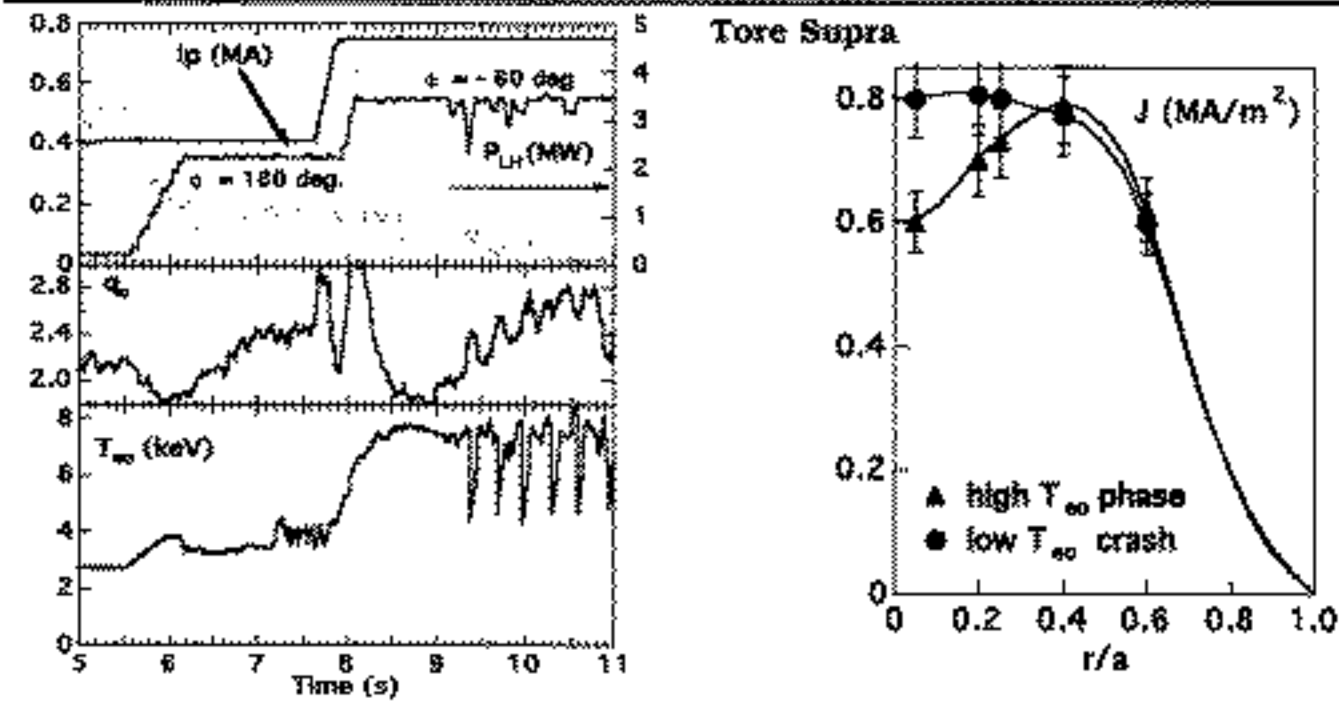
one or several final states?

Current profile misalignment :
q_0 and T_{e0} relaxation in full current drive operation



Equipe Tore Supra, 1996, Plasma Phys. Control. Fusion **38** A251.

2nd Top. Conf. on RF heating, Brussels, 20-23 January, 1996   Xavier Litaudon   20

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A mechanism for the internal plasma relaxations without invoking MHD instabilities

The evolutions of T_e (r, t) and q (r, t) are non-linearly coupled through:

i) χ_e (r, t) on S_m, and

ii) J_{LH}, $J_{bootstrap}$ on T_e

The relaxation mechanism:

1) Non-monotonic q(r) $\rightarrow$ core transport barrier + high T_{eo},

2) High T_{eo} $\rightarrow$ J_{LH} + $J_{bootstrap}$ $\nearrow$ inside the transport barrier $\rightarrow$ q(r) eventually reverts to a monotonic shape,

3) T_{eo} $\searrow$, J_{LH} + $J_{bootstrap}$ $\searrow$ inside the transport barrier $\rightarrow$ non-monotonic q(r) is formed again

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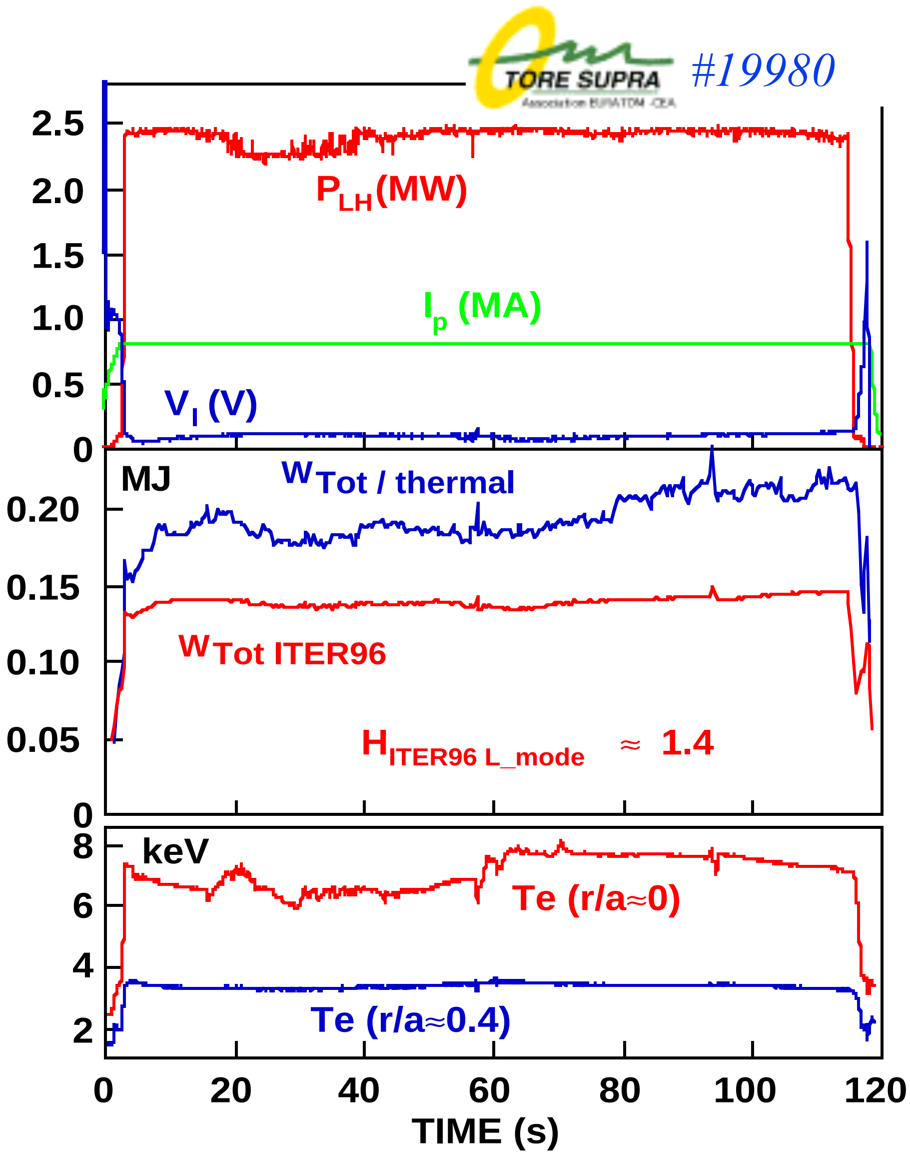
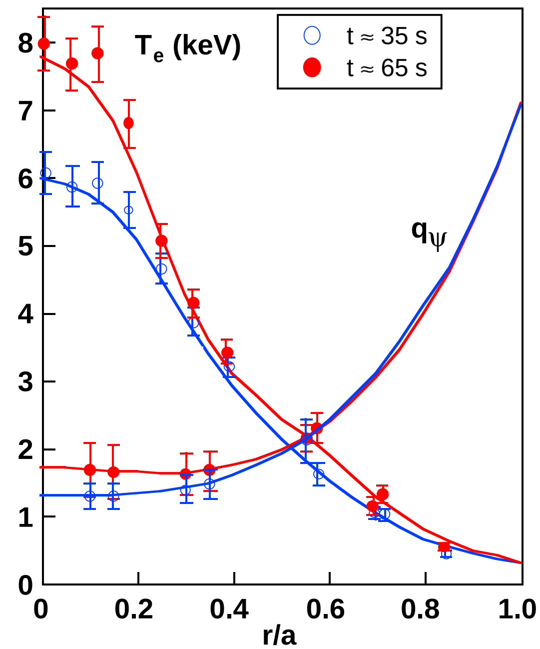
The non-inductive CD methods



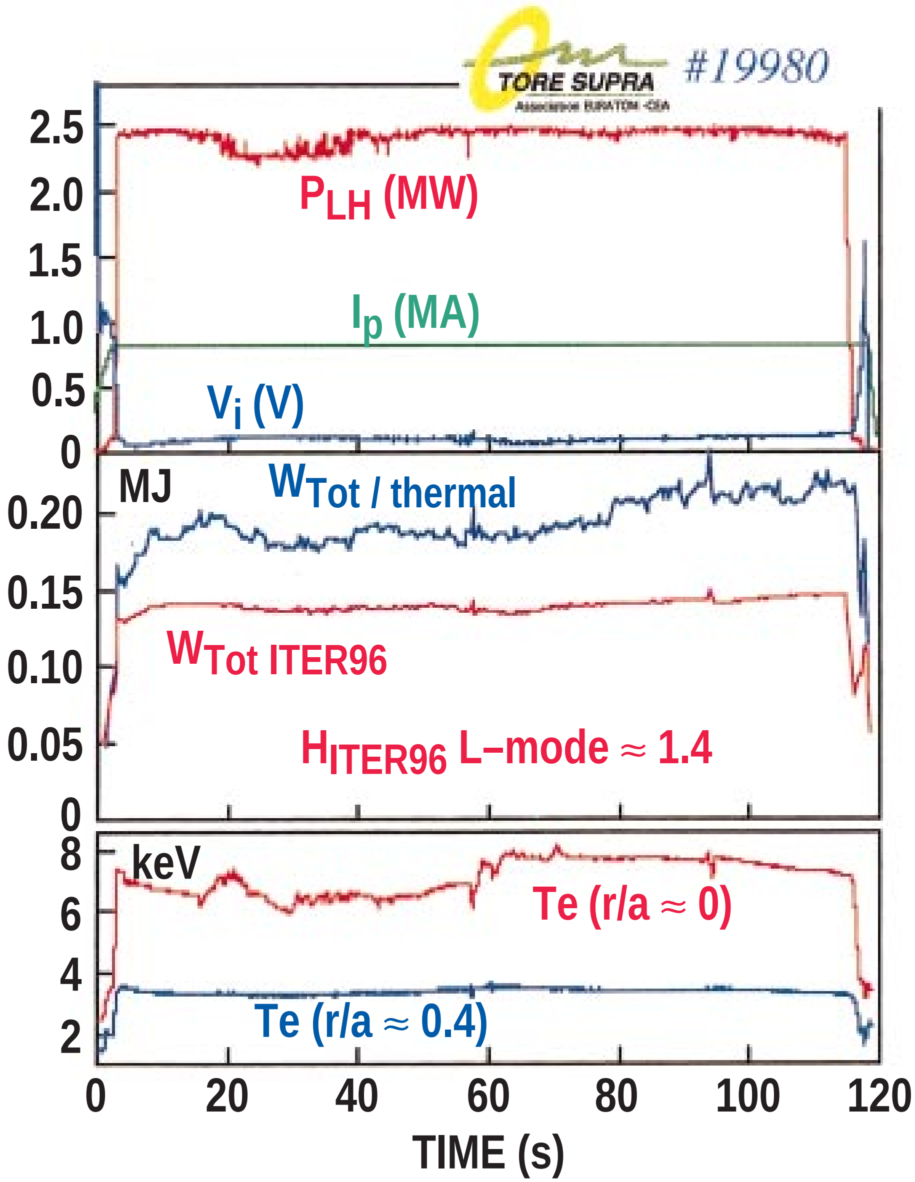
2.4MW LHCD

for 112 s



Equipe Tore Supra,
Plasma Phys. Control. Fusion 38 (1996) A251.

The non-inductive CD methods



2.4MW LHCD
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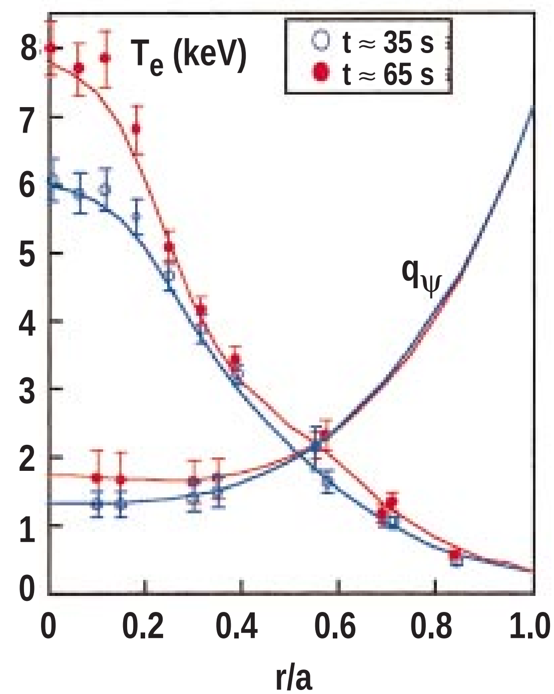
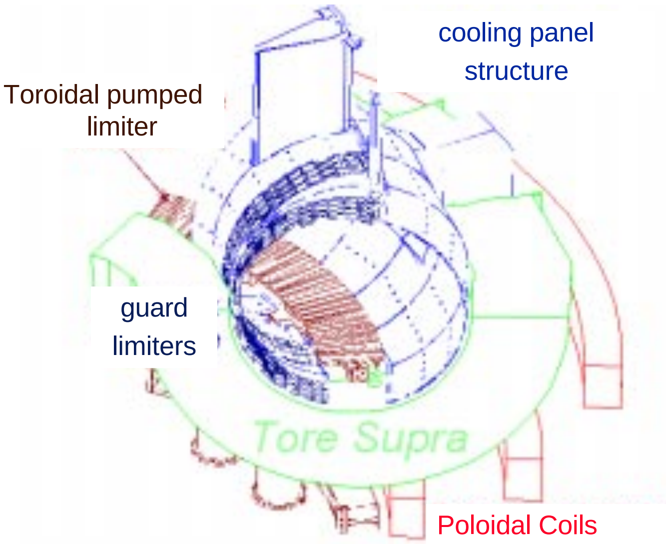


Equipe Tore Supra,
Plasma Phys. Control. Fusion 38 (1996) A251.

The Tore Supra CIEL project



Internal Components

& Limiter

(being built,

installed FY00)

H&CD

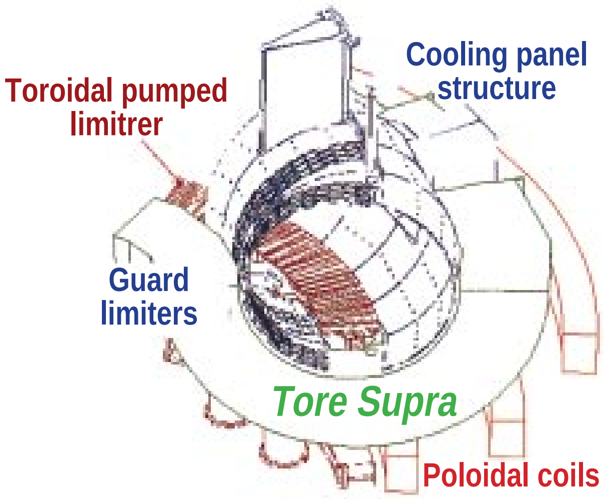
systems

(being designed)

	generator(99)	coupled(->98)	required (on plasma)
ICRF	12MW(30s)	10MW(2s) 6MW(30s)	10-12MW CW
LHCD	6 MW (210s)	5.3MW(6s) 2.4MW(112s)	6-8 MW CW
ECRF	0.5MW (210s)	-	2-3 MW CW

The Tore Supra CIEL project

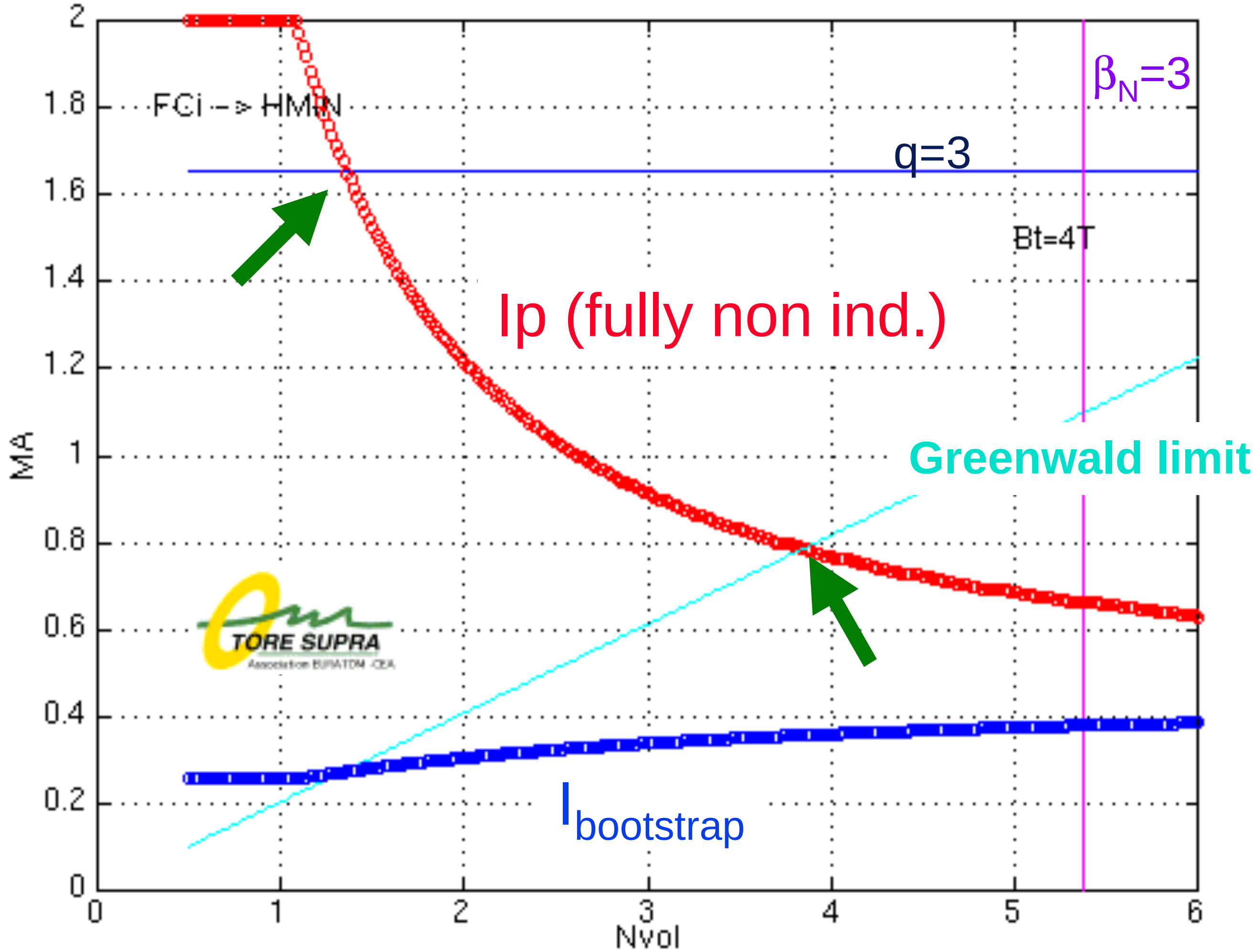
Internal Components
and Limiter
(being built,
installed FY00)



H&CD systems (being designed)

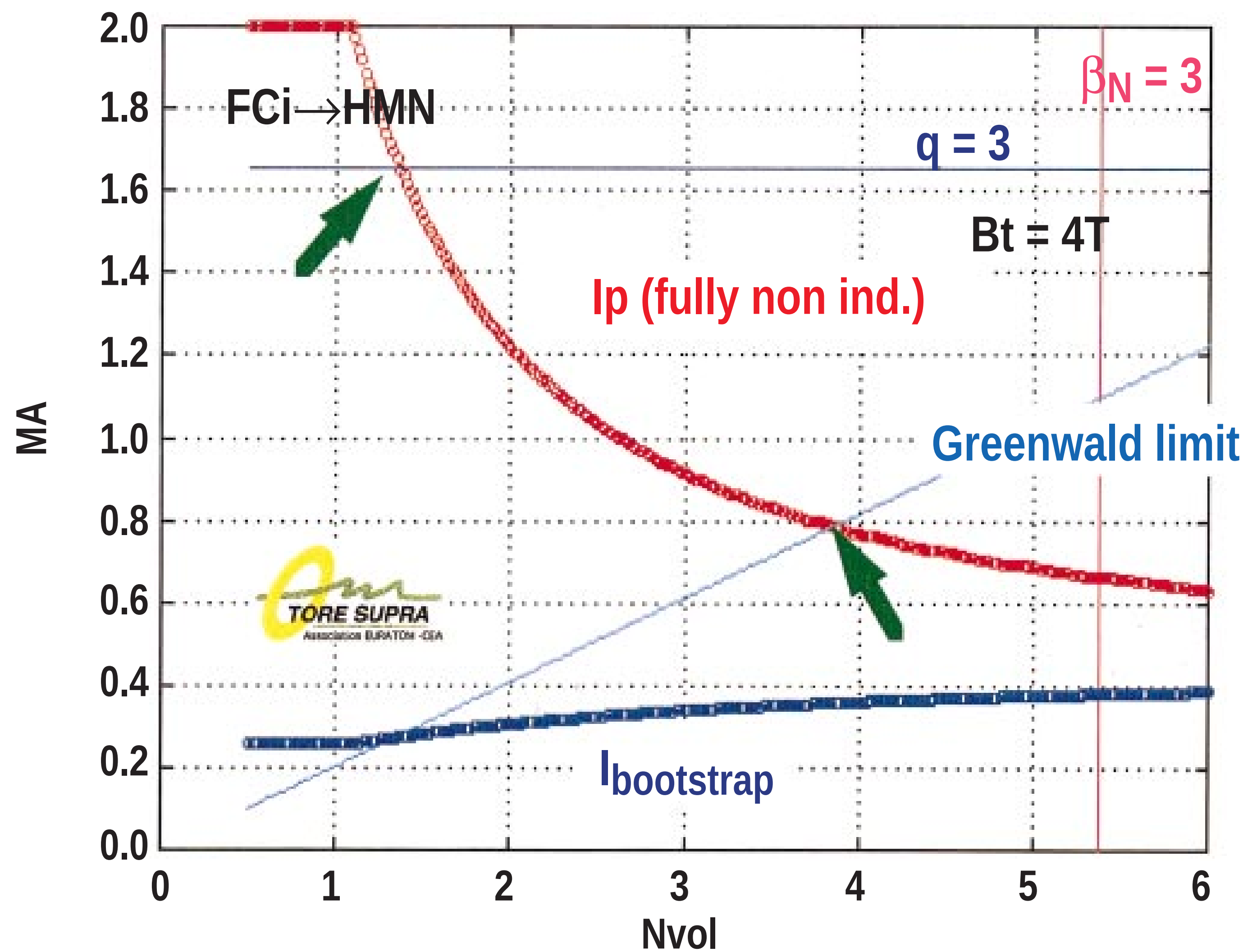
	Generator (99)	Coupled (->98)	Required (on plasma)
ICRF	12 MW (30s)	10 MW (2s) 6 MW (30s)	10–12 MW CW
LHCD	6 MW (210s)	5.3 MW (6s) 2.4 MW (112s)	6–8 MW CW
ECRF	0.5 MW (210s)	–	2–3 MW CW

8MW LHCD + 10MW ICRH + 2MW ECRH, B=4T



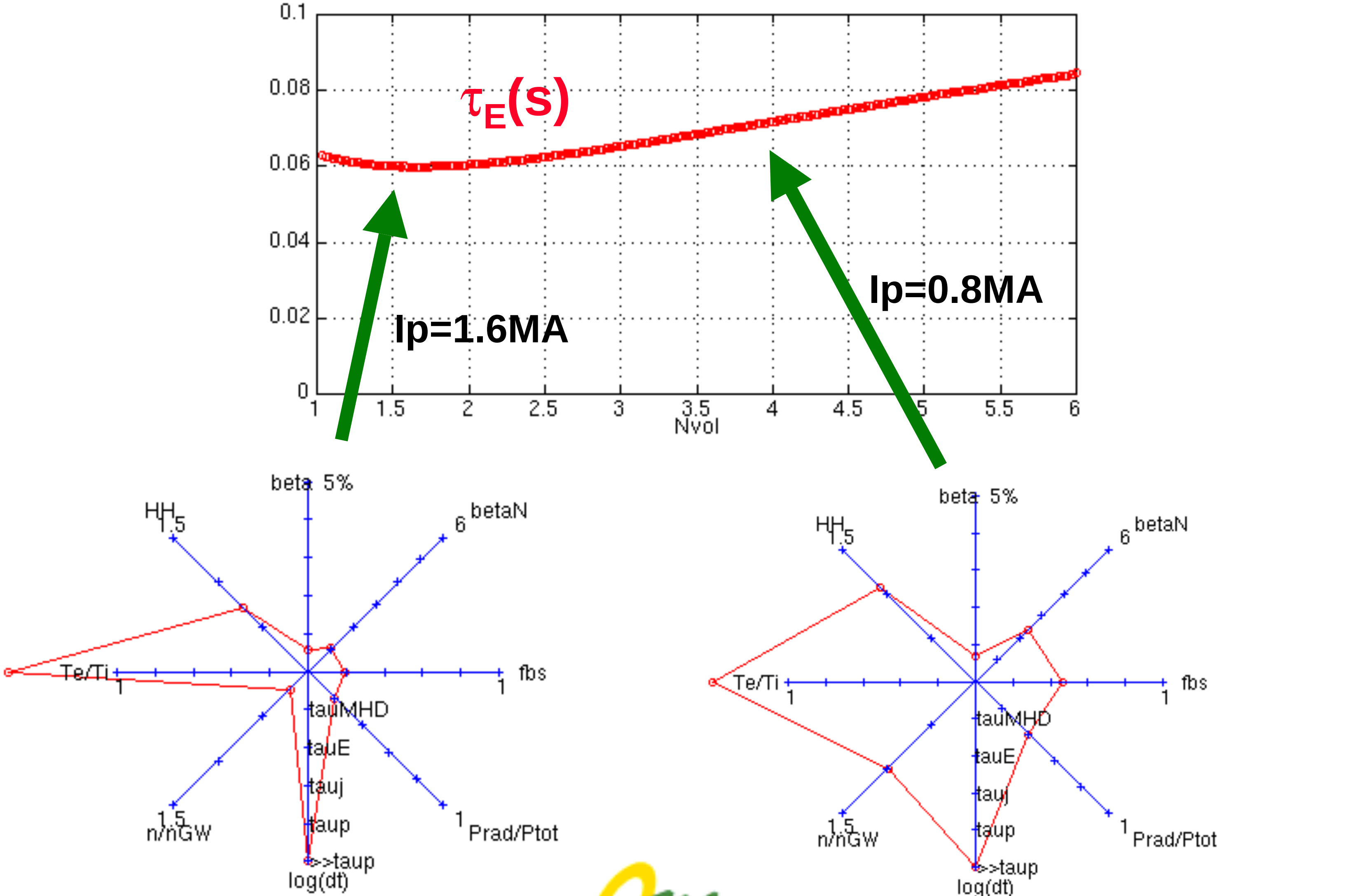
cf A. Bécoulet et al, 13th Top. RF Conf., Annapolis

8MW LHCD + 10MW ICRH + 2MW ECRH, B = 4T

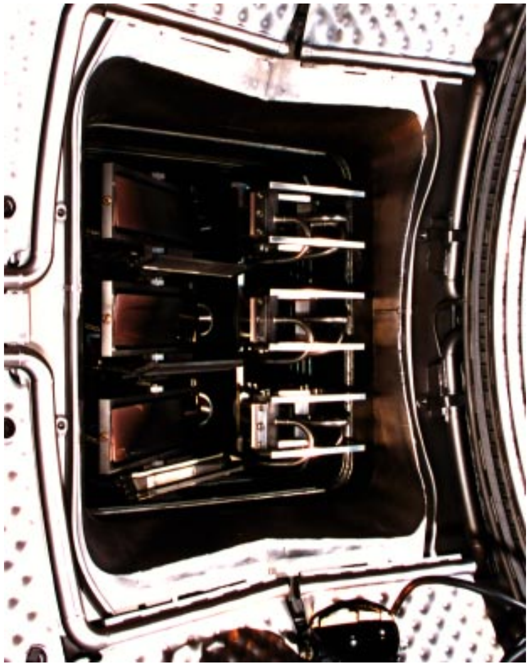


cf A. Bécoulet et al, 13th Top. RF Conf., Annapolis

Tokamak Performance Envelope



ECRH on TORE SUPRA



- 1 prototype 500kW gyrotron on site
- 1 antenna (3x2) in the machine
- 118 GHz
- Active cooling
- 6 x 500kW gyrotrons
- 210s capability

- on- & off-axis ECRH/ECCD
- MHD control

cf G. Giruzzi et al, 13th Top. RF Conf., Annapolis

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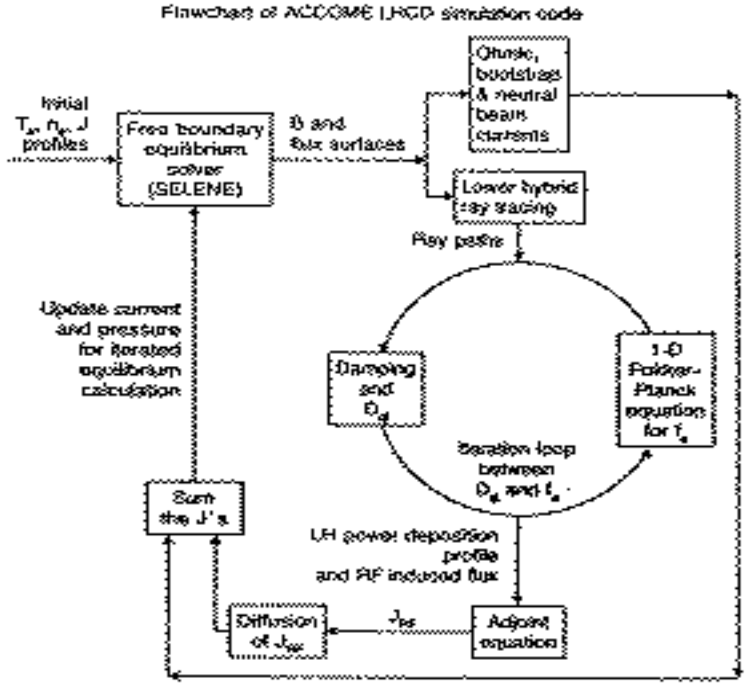
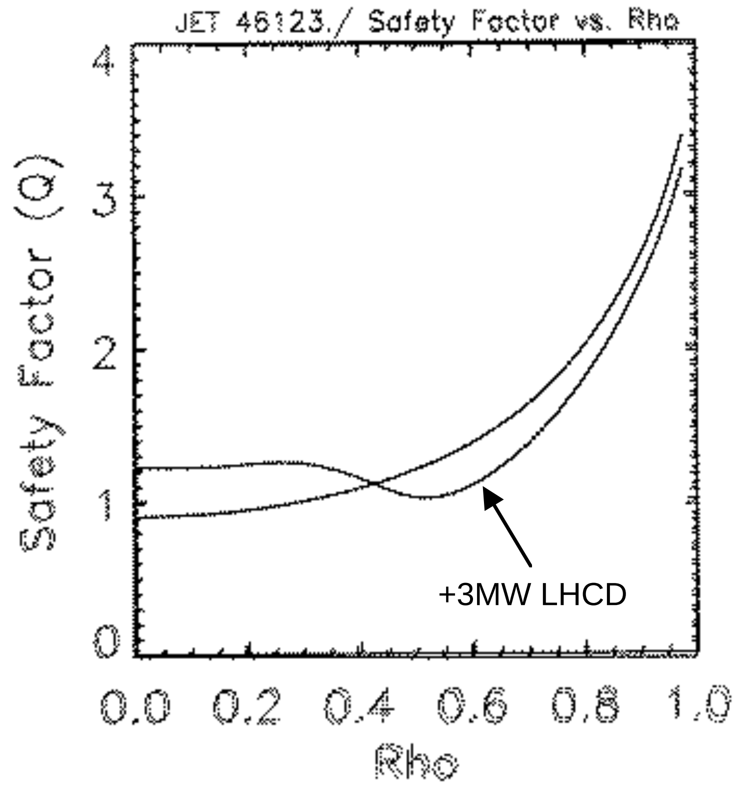
The JET case

ACCOME "analyzer for current drive consistent with MHD equilibrium"

(a) Free-boundary toroidal equilibrium solver
(b) Ohmic, bootstrap and neutral beam driven currents
(c) Lower hybrid physics package
— Ray tracing,
— 1-D Fokker–Planck equation with $T_\perp$ model,
— 'Adjoint' equation with fully relativistic bounce averaged collision operator,
— Spatial diffusion of RF current density.
(d) will add full wave ICRF module "TORIC"

Flowchart of ACCOME LHCD simulation code

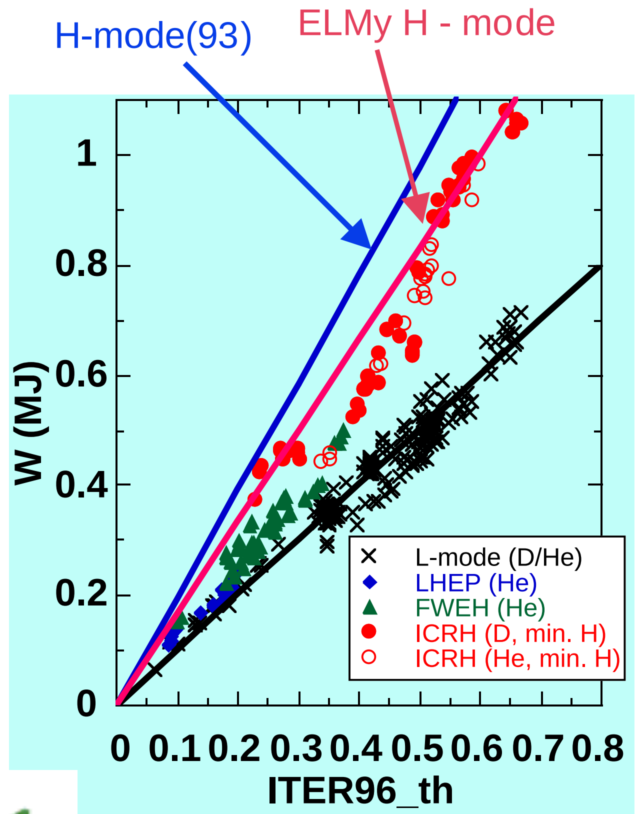




Ti ≠ Te : the role of the heating scheme

- high H-minority ICRH
- high density (->80% Greenwald)

-> increased plasma rotation
-> electron and ion
energy improvement



The role of the heating scheme (2)

• ***ICRH vs NBI* on JET :**

purpose: decoupling heating, fuelling, rotation

- (D)T scenario: efficient ion heating

- (^{3}He)DT scenario: suitable for reactor

(cf Bergeaud, Eriksson, Start, to be published in Nucl. Fus)

• ***ICRH + NBI* on JET :**

purpose: balancing Ti & Te

purpose: presence of fast ions above Wcrit

- strong electron heating

- simulation of alphas

purpose: controling the power dep. profile

- bootstrap alignment

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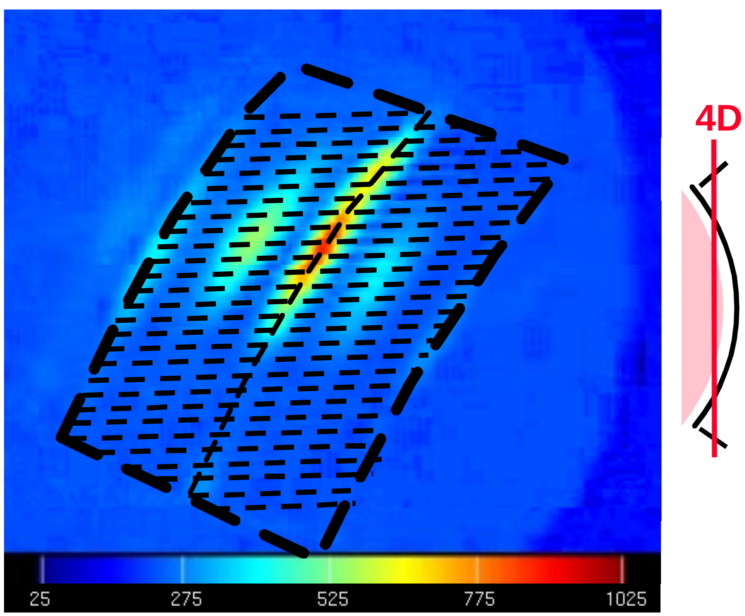
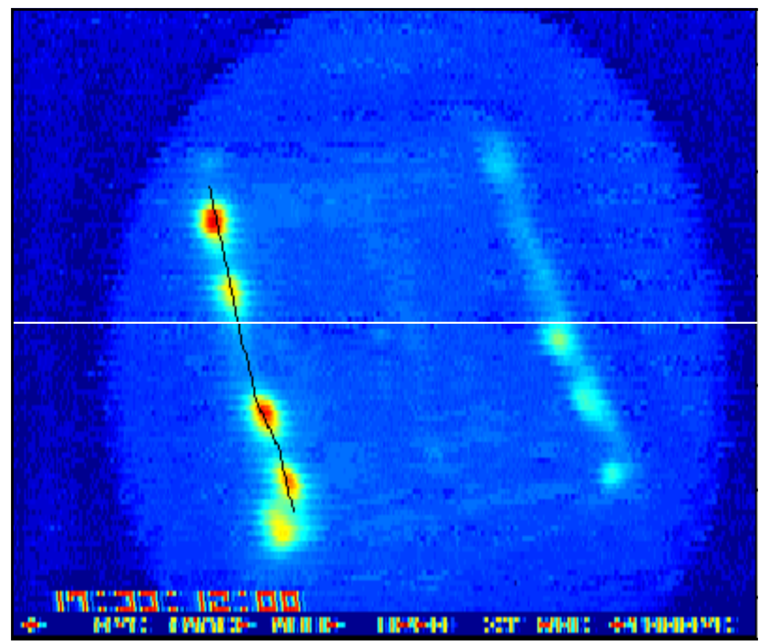
Long pulse discharges involving RF: the problem of power coupling

- maximisation of the coupled power
- reliable pulses: arc detection and safety systems
- edge physics:

ICRF on TORE SUPRA



LHCD on TORE SUPRA

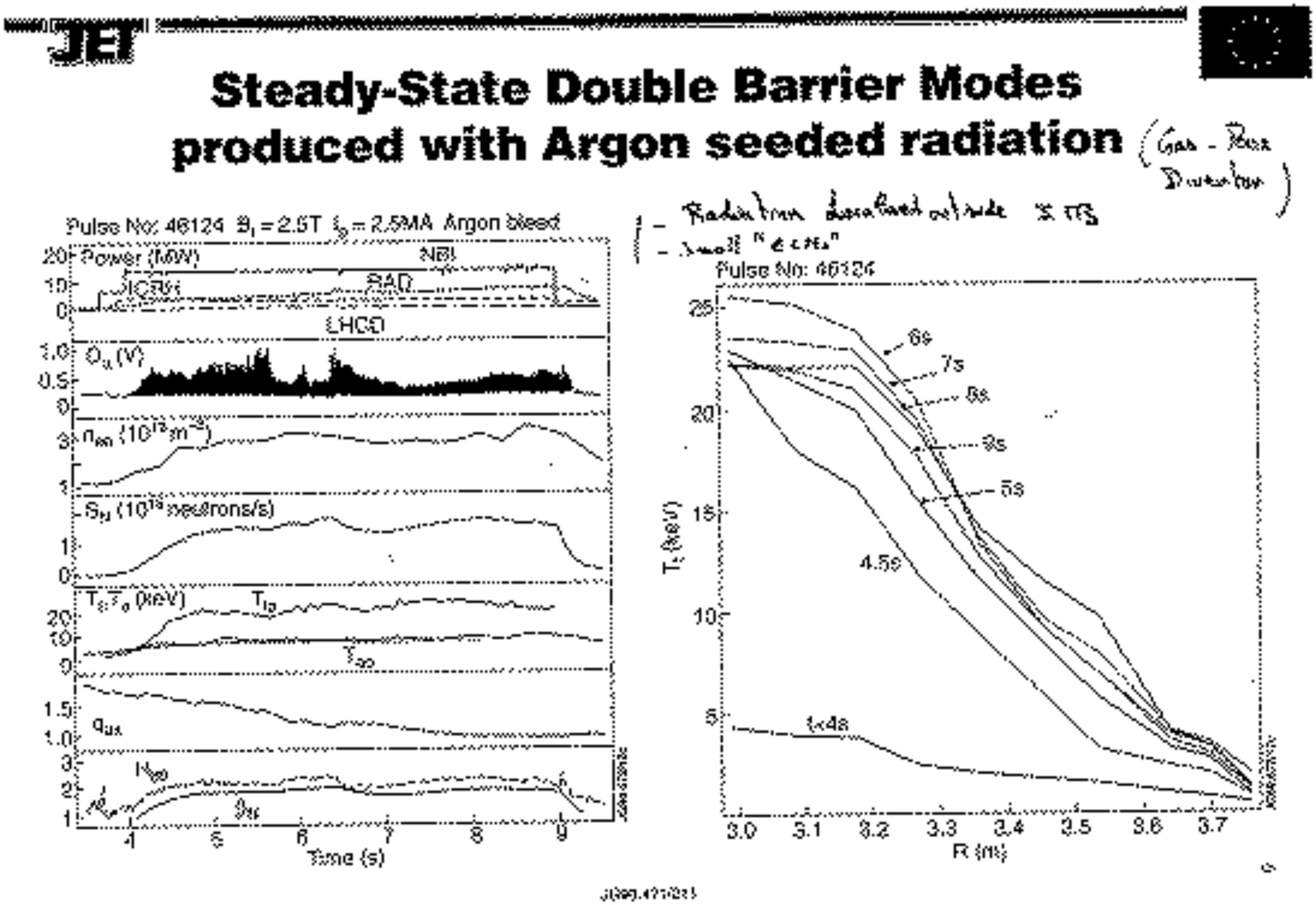


Which edge for steady-state operation?

L-mode	H-mode
↑ good RF coupling (λn, no ELM)	↑ supplementary H-factor
	↑ higher β_N-limit
	↑ edge bootstrap
↓ lower β_N-limit	↓ lower RF coupling (λn, ELMs)
	↓ ELMs (heat load)
	↓ pedestal weakening ITB
	↓ edge bootstrap

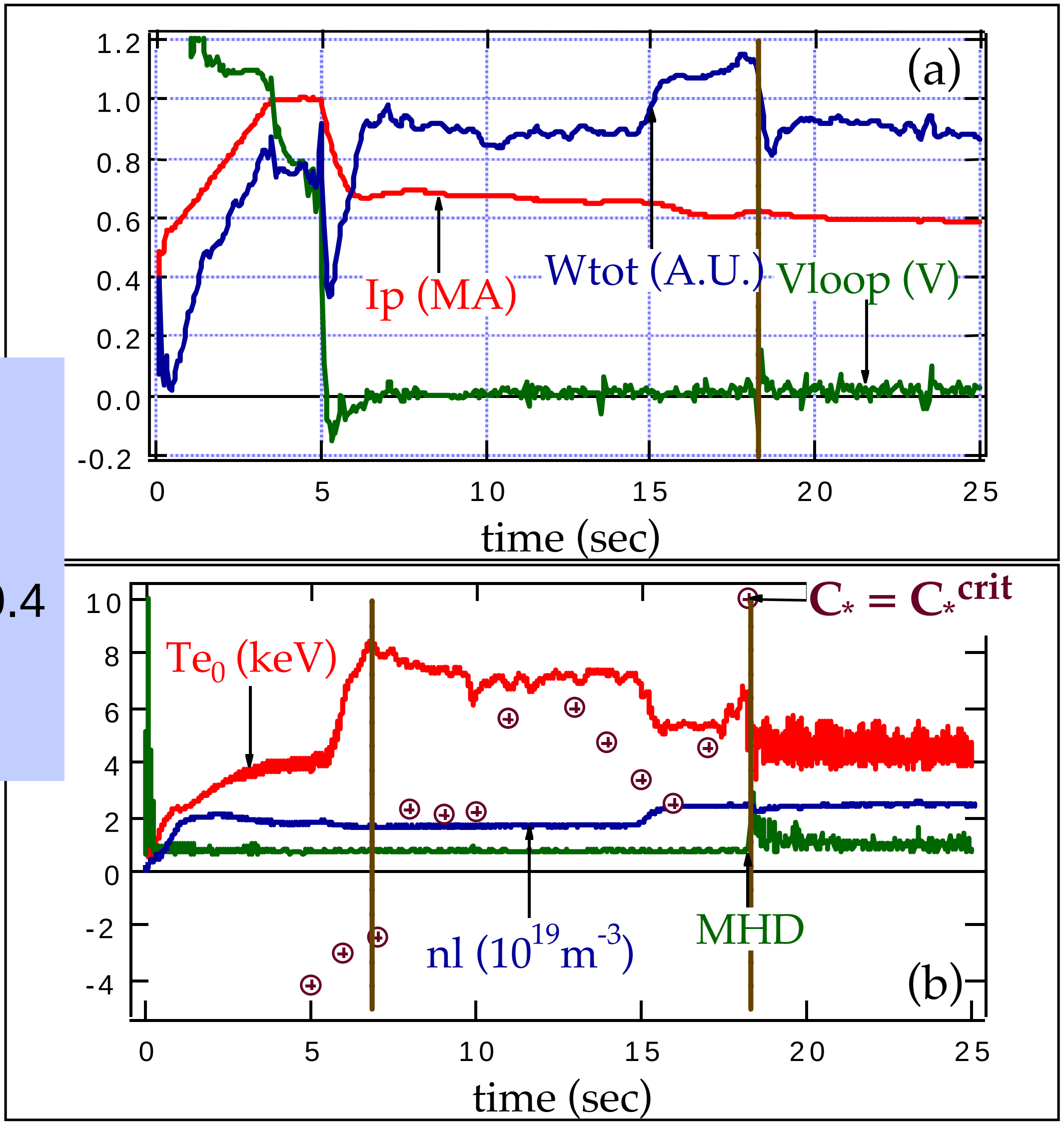
=> Wide ITBs in L-mode edge (?)

Argon bleed in JET



long term MHD evolution

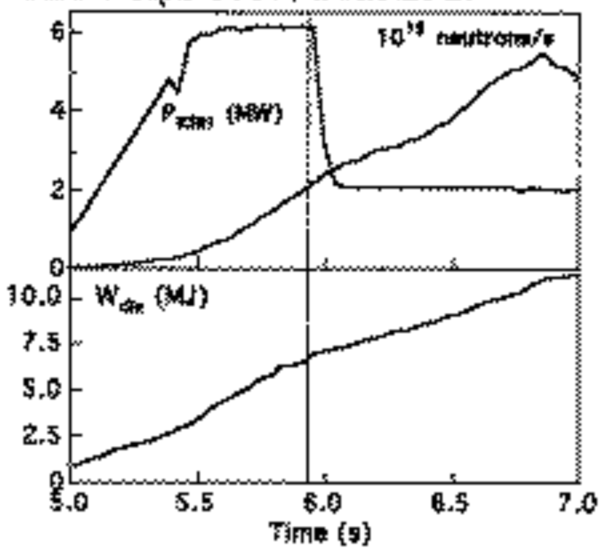
- zero loop-voltage
  LHCD discharge
- weak central magnetic shear
- tearing modes at t=18s, β_N=0.4
- m/n=2/1+ m/n=3/1
  "sawtooth-like" activity.

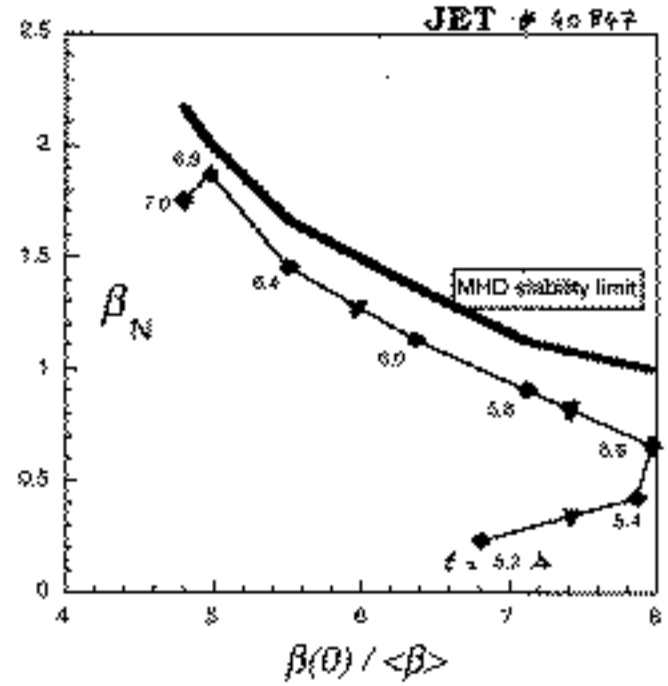


MHD on JET

Pressure feedback control with on-axis ICRH heating to prevent excessive pressure peaking

- **JET** : Sips 1997, 24th EPS.





Huysmans1997 24th EPS. Berchtesgaden.

- DIII-D :

trigger L to H transition

[Lazarus 1996, PRL 2714]

2nd Top. Conf. on RF heating, Brussels, 20-23 January, 1998 — Xavier Litaudon — 26

Controlling steady-state "AT" discharges

- **Current and pressure profile controls**
  => multiple H/CD sources for flexibility
  => significant power and coupling margins
  => algorithms (i.e. diagnostics and modelling)
- **Particle fluxes**
  => multi-pellet injection (reliability?)
  => significant pumping capability
  => impurity (and ashes) control
- **Heat Exhaust**

Requirements on modelling activity

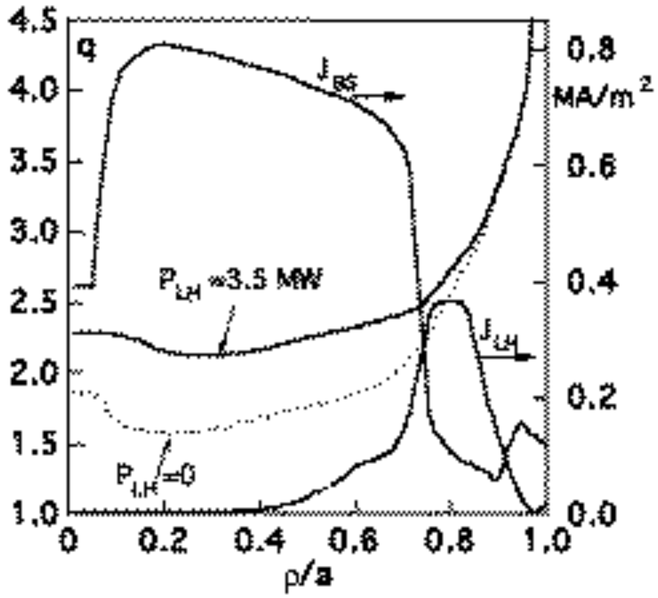
Towards self-consistent time dependant modelling:

heating & current drive, transport and MHD stability

=> determination of the route to steady-state

JET : "Optimised shear" regime + ELM'y H mode

I_p ≈ 3.1 MA / 3.4 T
$P_{ICRH} + P_{NBI}$ = 21(4+17) MW



Time dependent and consistent modelling : transport, Heating and current-drive, MHD stability.

Profile control with off-axis LH current drive :

- **βN-Limit ≈ 2.5 → 3.2**
- **Vloop ≈ 0**
- **I_{boot}/I_p ≈ 65%**
- **wider ITB ?**

High-power phase t ≤ 5s

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2nd Top. Conf. on RF Heating, Brussels, 20-23 January, 1998 Xavier Litaudon 29

Conclusions and perspectives (1)

Demonstrating the steady-state capability of "AT" discharges implies:

- to achieve performant discharges (H, β_N, Q, ITBs, ...)
- to perform such discharges at Vloop=0
  with a significant bootstrap fraction
- to achieve a satisfying particle and impurity confinement
- to achieve stable state(s) (ITB location, MHD, edge)
  & control the profiles of pressure, current & density.
- to develop active controls against MHD events, ...

Extension of such regimes towards reactor requires:

- to find a route to high-Q regimes in "AT"
- to perform them at higher densities, and balanced Ti-Te
- to prove the compatibility with alpha particles (profiles, MHD, ...)
- to demonstrate the control capability in presence of alpha particles.

Conclusions and perspectives (2)

The TORE SUPRA program will address in the coming years the following points:

- steady-state discharges (->1000s) combining RFCD and bootstrap
- heat exhaust: limiter(->15MW) + radiated power(->10MW)
- active current, pressure, MHD feedback controls
- active fuelling and particle exhaust
- fast ion&electron behaviour studies
- RF power coupling in CW
- Modelling

The JET program could address:

- the sustainement of high-performance ITBs on resistive times.
- balanced Te-Ti regimes
- active current, pressure, MHD feedback controls
- the role of alpha particles (simulated or in D-T shots)