History of research into confinement improvement

F. Wagner

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Special issue:

Plasma physics in the 20th century as told by players

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THE EUROPEAN
PHYSICAL JOURNAL H

The history of research into improved confinement regimes

F. Wagner[a]

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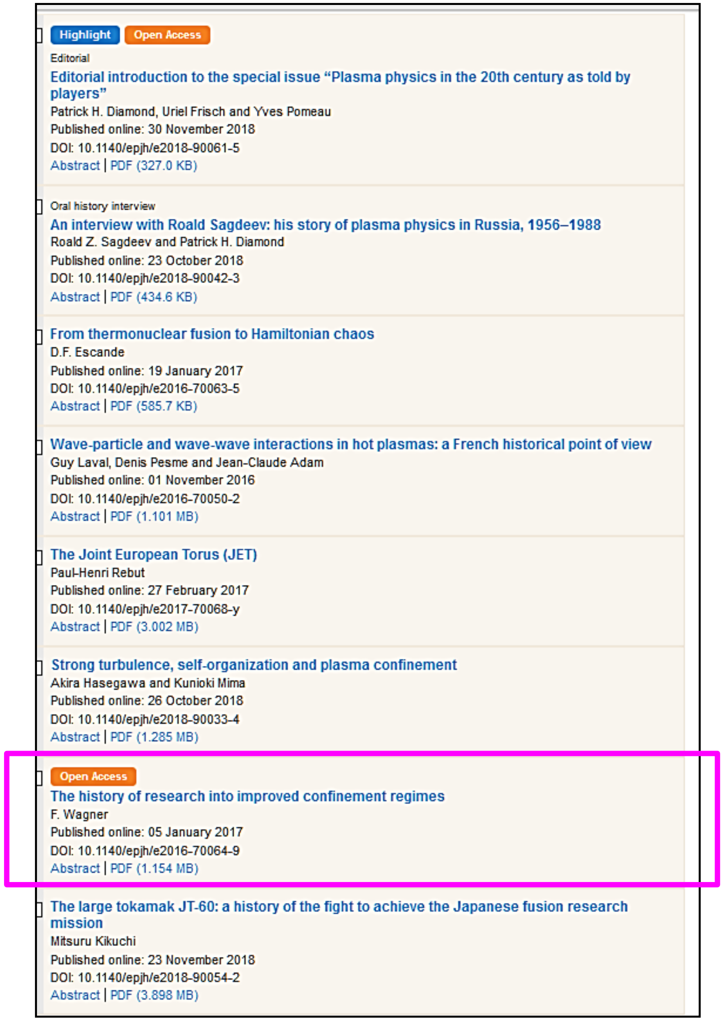
Received 9 November 2016
Published online 5 January 2017

Abstract. Increasing the pressure by additional heating of magnetically confined plasmas had the consequence that turbulent processes became more violent and plasma confinement degraded. Since this experience from the early 1980ies, fusion research was dominated by the search for confinement regimes with improved properties. It was a gratifying experience that toroidally confined plasmas are able to self-organise in such a way that turbulence diminishes, resulting in a confinement with good prospects to reach the objectives of fusion R&D. The understanding of improved confinement regimes revolutionized the understanding of turbulent transport in high-temperature plasmas. In this paper the story of research into improved confinement regimes will be narrated starting with 1980.



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Editorial
Editorial introduction to the special issue “Plasma physics in the 20th century as told by players”
Patrick H. Diamond, Uriel Frisch and Yves Pomeau
Published online: 30 November 2018
DOI: 10.1140/epjh/e2018-90061-5
Abstract | PDF (327.0 KB)

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An interview with Roald Sagdeev: his story of plasma physics in Russia, 1956–1988
Roald Z. Sagdeev and Patrick H. Diamond
Published online: 23 October 2018
DOI: 10.1140/epjh/e2018-90042-3
Abstract | PDF (434.6 KB)

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D.F. Escande
Published online: 19 January 2017
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Guy Laval, Denis Pesme and Jean-Claude Adam
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Paul-Henri Rebut
Published online: 27 February 2017
DOI: 10.1140/epjh/e2017-70068-y
Abstract | PDF (3.002 MB)

Strong turbulence, self-organization and plasma confinement
Akira Hasegawa and Kunioki Mima
Published online: 26 October 2018
DOI: 10.1140/epjh/e2018-90033-4
Abstract | PDF (1.285 MB)

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The history of research into improved confinement regimes
F. Wagner
Published online: 05 January 2017
DOI: 10.1140/epjh/e2016-70064-9
Abstract | PDF (1.154 MB)

The large tokamak JT-60: a history of the fight to achieve the Japanese fusion research mission
Mitsuru Kikuchi
Published online: 23 November 2018
DOI: 10.1140/epjh/e2018-90054-2
Abstract | PDF (3.898 MB)

Importance of the energy confinement time τ_E

A burning fusion reactor has to meet the $<n><T>\tau_E$ – condition: ~ 10^{20} m^3 10 keV 3 sec

→ a high confinement time τ_E is the key to a fusion reactor

Power balance under steady-state: $3/2 <n><T> Vol = (P_{fus}+P_{aux})\ \tau_E$

Confinement and transport: $W/\tau_E = - n\ \chi$ gradT surface $\rightarrow \tau_E \sim a^2/\chi$

χ is the heat diffusivity

heat is transported via Coulomb-collisions and by turbulence

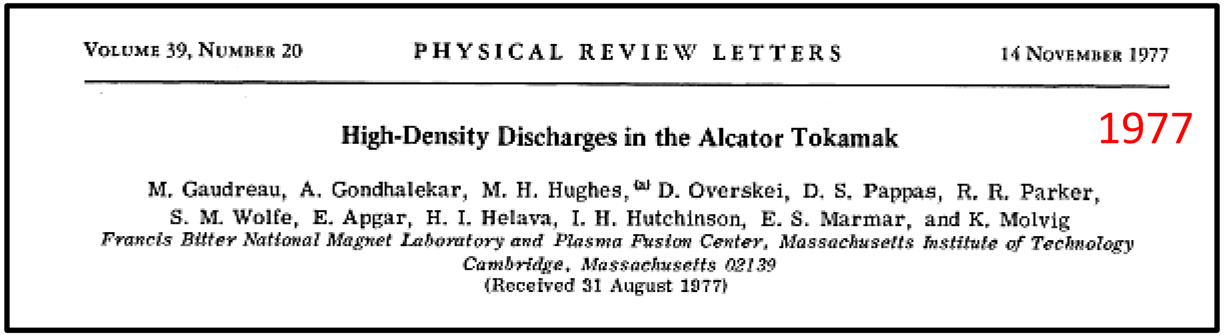
apart from exotic conditions, τ_E is governed by plasma turbulence (also τ_p, τ_Φ)

Though there is tremendous progress in understanding transport,
predictions are still vague – e.g. what will be the confinement time of ITER?

→ statistical analysis and empirical scaling rules provide τ_E values

The first τ_E scaling of relevance: Alcator-A ohmic scaling

Neo-Alcator scaling: Middle of the 70ies



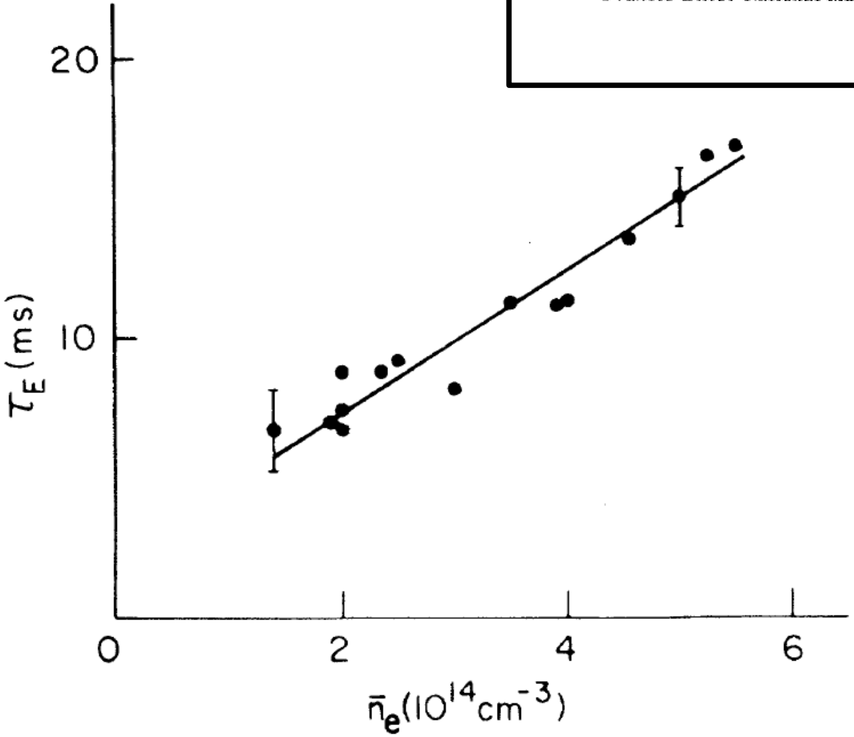
VOLUME 39, NUMBER 20 PHYSICAL REVIEW LETTERS 14 NOVEMBER 1977

High-Density Discharges in the Alcator Tokamak

1977

M. Gaudreau, A. Gondhalekar, M. H. Hughes,[a] D. Overskei, D. S. Pappas, R. R. Parker,
S. M. Wolfe, E. Apgar, H. I. Helava, I. H. Hutchinson, E. S. Marmar, and K. Molvig
Francis Bitter National Magnet Laboratory and Plasma Fusion Center, Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

(Received 31 August 1977)

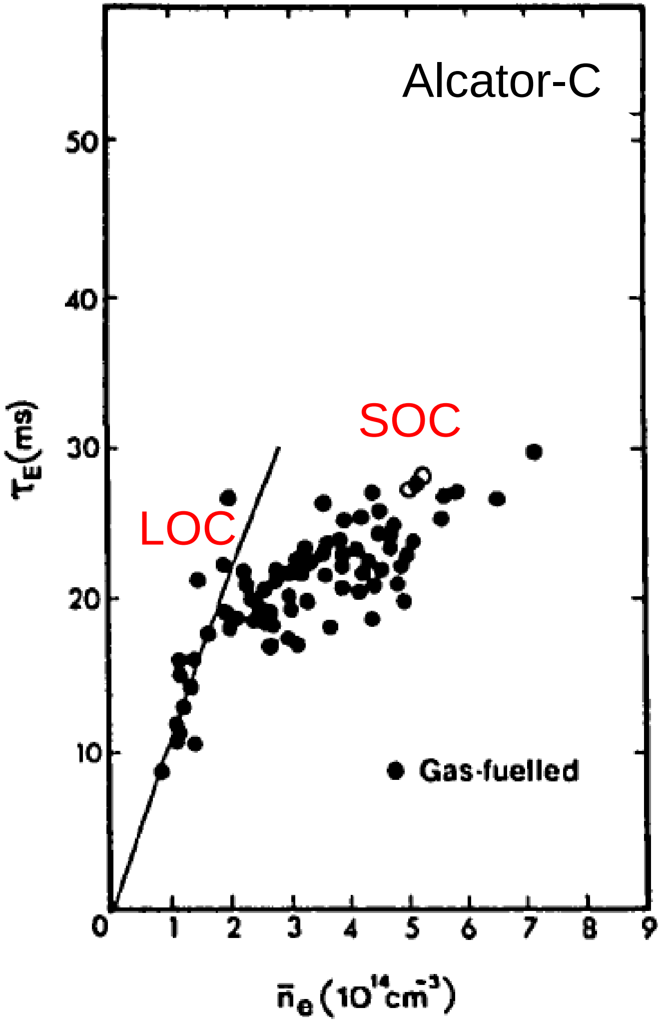


$\tau_E \sim n_e$:

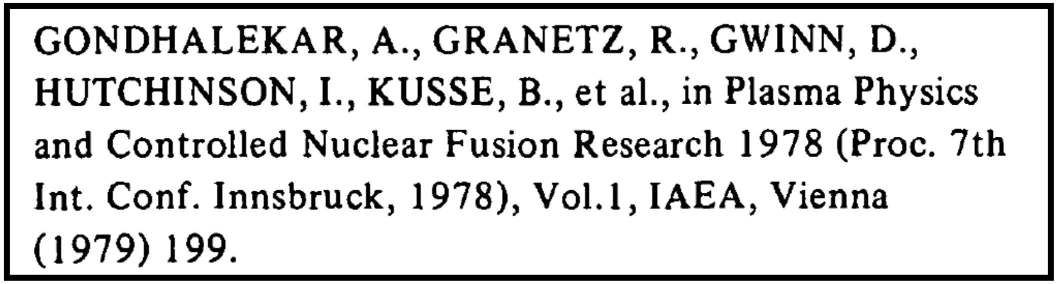
favourable scaling because fusion product n $\tau_E \sim n^2$

The first disappointment: the SOC regime

τ_E saturates toward higher densities



First communicated 1978:



GONDHALEKAR, A., GRANETZ, R., GWINN, D., HUTCHINSON, I., KUSSE, B., et al., in Plasma Physics and Controlled Nuclear Fusion Research 1978 (Proc. 7th Int. Conf. Innsbruck, 1978), Vol.1, IAEA, Vienna (1979) 199.

The causes for the τ_E-saturation

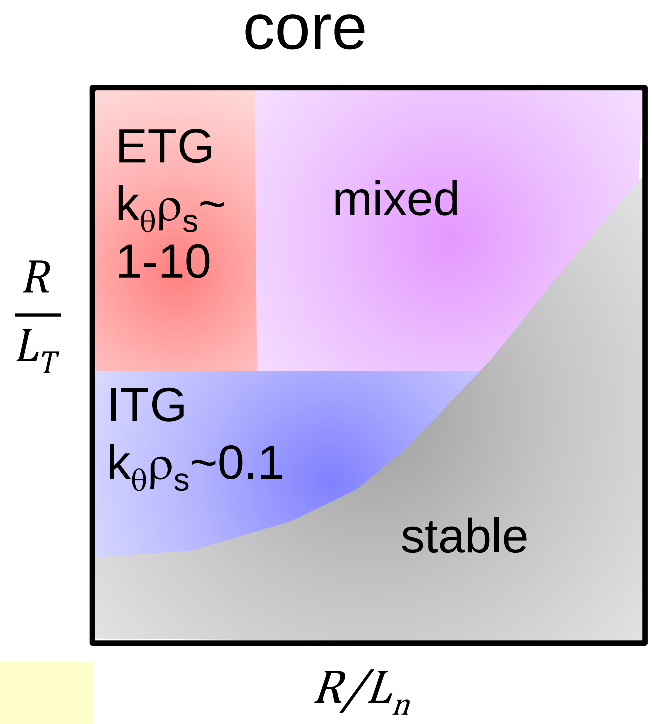
This question needs the understanding of turbulent transport

energy is transported by potential fluctuations in the plasma causing fluctuating drifts

basic electrostatic instabilities : **drift waves**

Driving forces: gradients

- ∇T_e: ETG (electron-temp. gradient-mode, core)
- ∇T_i: ITG-mode (ion-temp. gradient-mode, core/edge)
- ∇n: TEM (trapped electron mode, edge)



k_θ = poloidal eddy wave vector
ρ_s = Larmor radius at ion sound velocity
R = major radius
L_n = n/∇n: density gradient length

after J. Weiland

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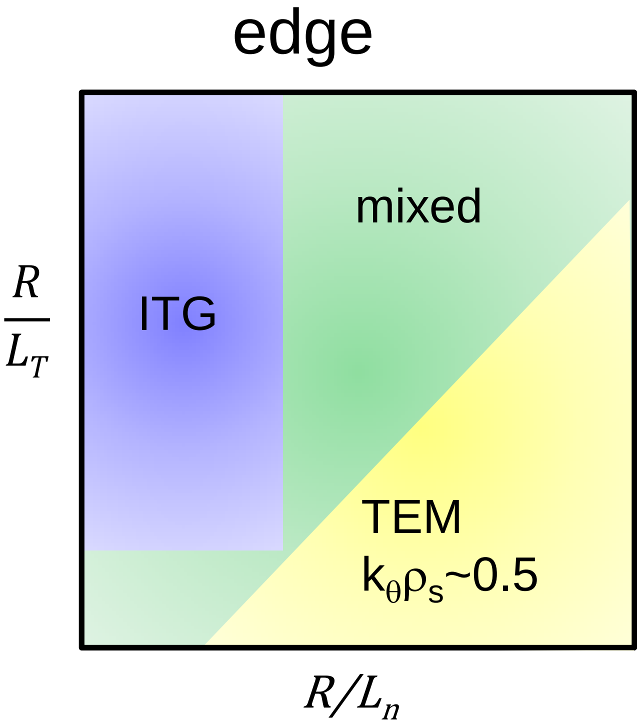

after J. Weiland

The causes for the τ_E-saturation

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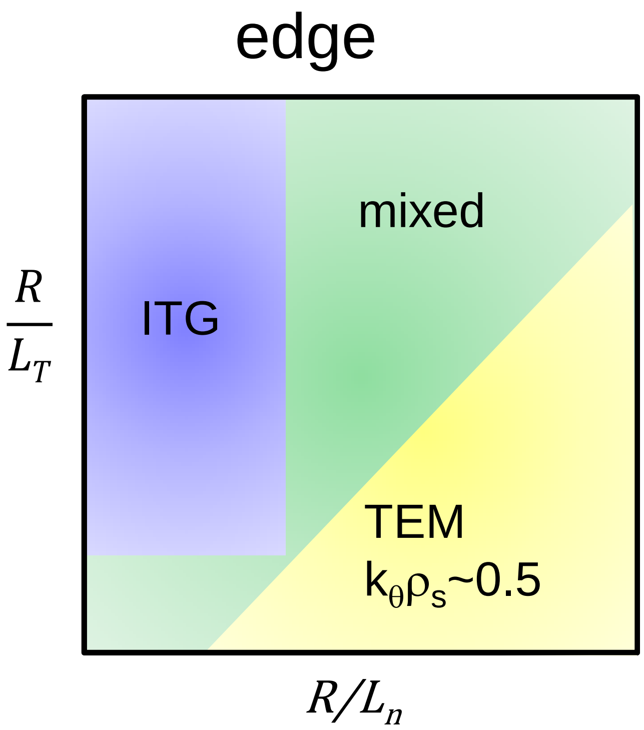
- ∇n: TEM (trapped electron mode, edge)

Reality more complex:

- critical onset gradients
- marginal stability conditions
- profile resilience
- development of large radial scales (streamers)
- zonal flows (ZF, GAMs)

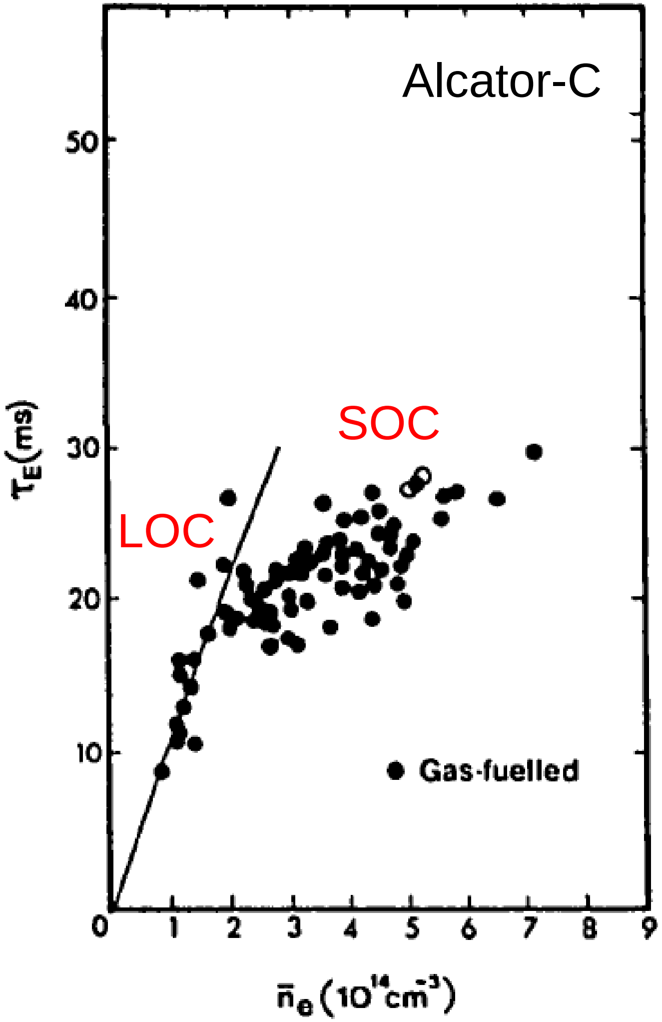
Important parameters:

- q, shear, reversed shear
- collisionality, Z_{eff}, T_e/T_i, fast particles



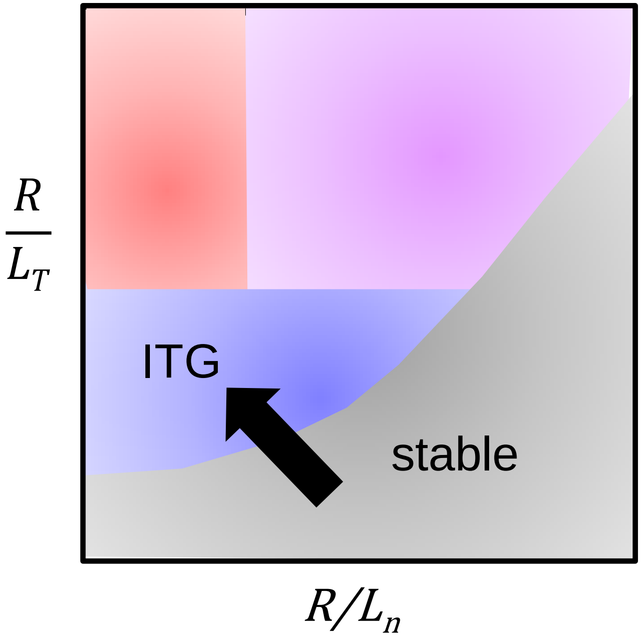
after J. Weiland

The causes for the τ_E-saturation



Towards higher density:

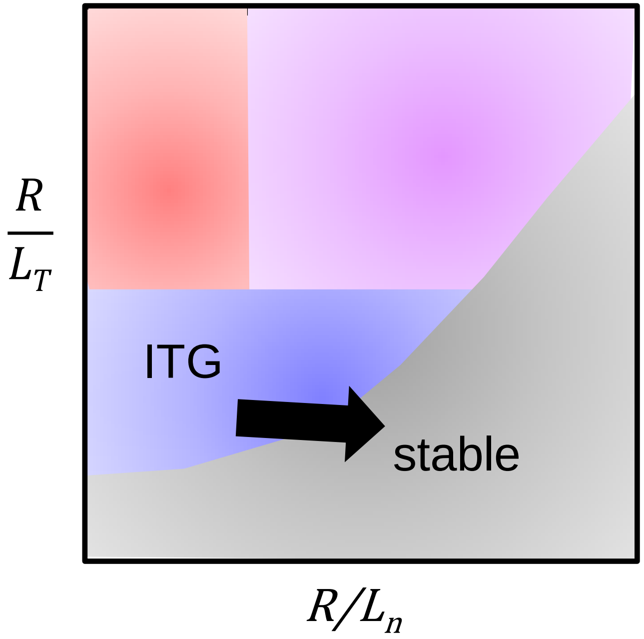
Ions are heated by electron collisions
Ion gradient increases
Density profile becomes flatter (source to edge)
ITG turbulence is enhanced



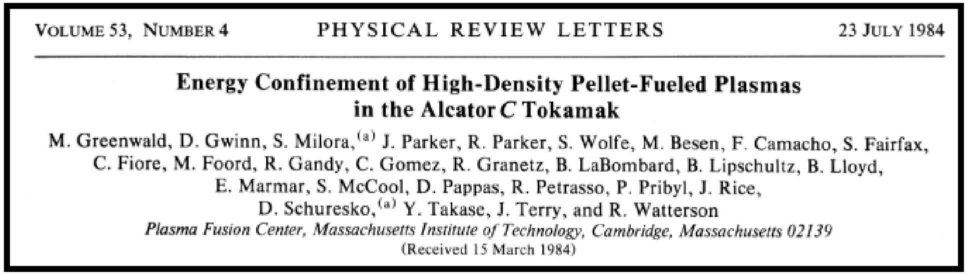
30 years later:
core toroidal rotation changes direction at
LOC → SOC

Ways to overcome this problem: external

Particle source to core by pellet fuelling



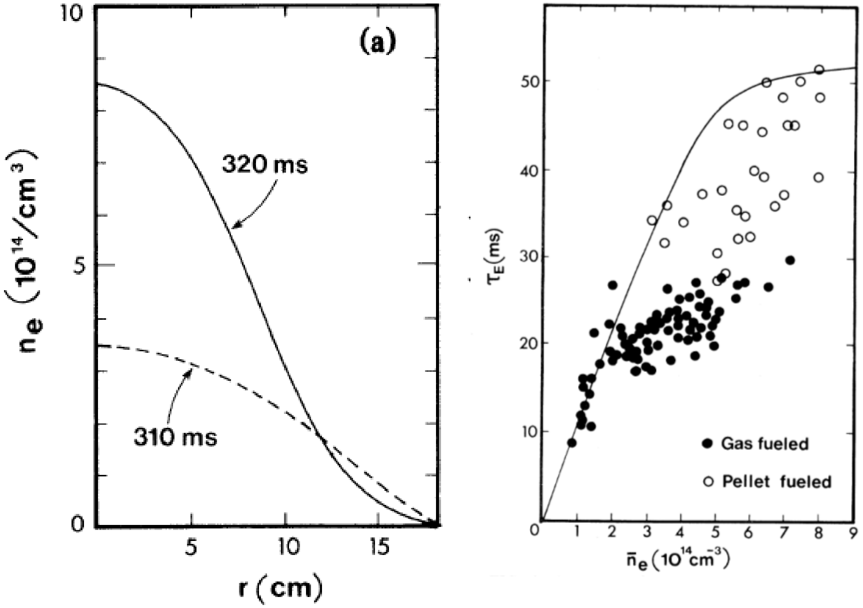
Pellet fuelling 1984



VOLUME 53, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1984

Energy Confinement of High-Density Pellet-Fueled Plasmas in the Alcator *C* Tokamak

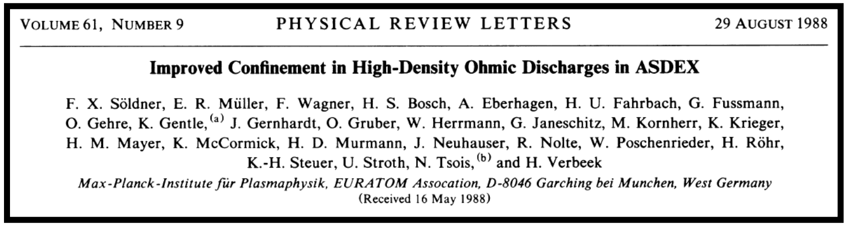
M. Greenwald, D. Gwinn, S. Milora,(a) J. Parker, R. Parker, S. Wolfe, M. Besen, F. Camacho, S. Fairfax,
C. Fiore, M. Foord, R. Gandy, C. Gomez, R. Granetz, B. LaBombard, B. Lipschultz, B. Lloyd,
E. Marmar, S. McCool, D. Pappas, R. Petrasso, P. Pribyl, J. Rice,
D. Schuresko,(a) Y. Takase, J. Terry, and R. Watterson
Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 15 March 1984)



important:
the improved state can be initiated

Ways to overcome this problem: internal

IOC-mode of ASDEX, 1988

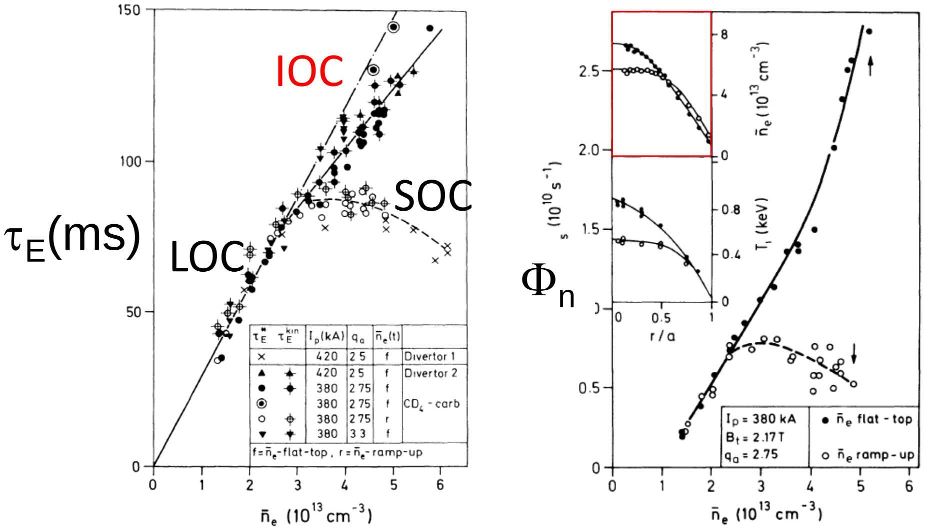


VOLUME 61, NUMBER 9 PHYSICAL REVIEW LETTERS 29 AUGUST 1988

Improved Confinement in High-Density Ohmic Discharges in ASDEX

F. X. Söldner, E. R. Müller, F. Wagner, H. S. Bosch, A. Eberhagen, H. U. Fahrbach, G. Fussmann, O. Gehre, K. Gentle,[a] J. Gernhardt, O. Gruber, W. Herrmann, G. Janeschitz, M. Kornherr, K. Krieger, H. M. Mayer, K. McCormick, H. D. Murmann, J. Neuhauser, R. Nolte, W. Poschenrieder, H. Röhr, K.-H. Steuer, U. Stroth, N. Tsois,[b] and H. Verbeek
Max-Planck-Institute für Plasmaphysik, EURATOM Assocation, D-8046 Garching bei Munchen, West Germany

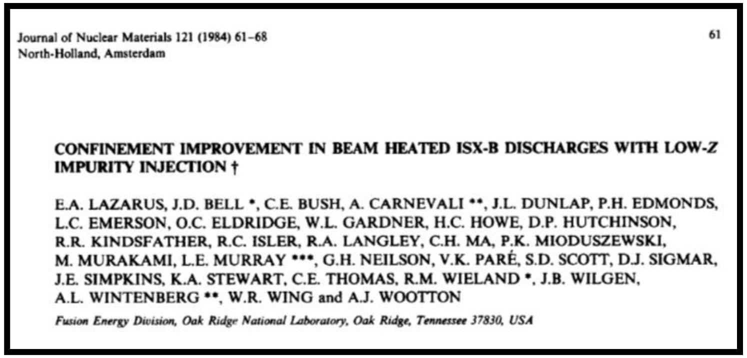
(Received 16 May 1988)



Self-induced improvement
Different branches: SOC-IOC
trick: change edge conditions by reducing edge fuelling

Ways to overcome this problem

Z-mode (ISX)-B-mode (T10)-RI-mode (TEXTOR)



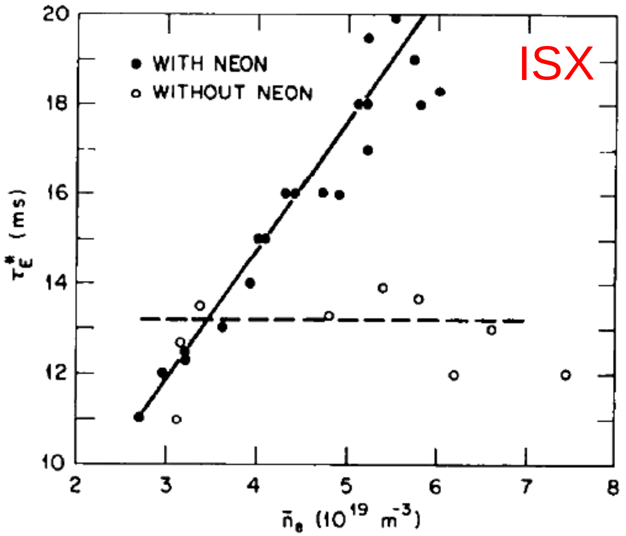
Journal of Nuclear Materials 121 (1984) 61–68
North-Holland, Amsterdam

61

CONFINEMENT IMPROVEMENT IN BEAM HEATED ISX-B DISCHARGES WITH LOW-Z IMPURITY INJECTION †

E.A. LAZARUS, J.D. BELL *, C.E. BUSH, A. CARNEVALI **, J.L. DUNLAP, P.H. EDMONDS, L.C. EMERSON, O.C. ELDRIDGE, W.L. GARDNER, H.C. HOWE, D.P. HUTCHINSON, R.R. KINDSFATHER, R.C. ISLER, R.A. LANGLEY, C.H. MA, P.K. MIODUSZEWSKI, M. MURAKAMI, L.E. MURRAY ***, G.H. NEILSON, V.K. PARÉ, S.D. SCOTT, D.J. SIGMAR, J.E. SIMPKINS, K.A. STEWART, C.E. THOMAS, R.M. WIELAND *, J.B. WILGEN, A.L. WINTENBERG **, W.R. WING and A.J. WOOTTON

Fusion Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA

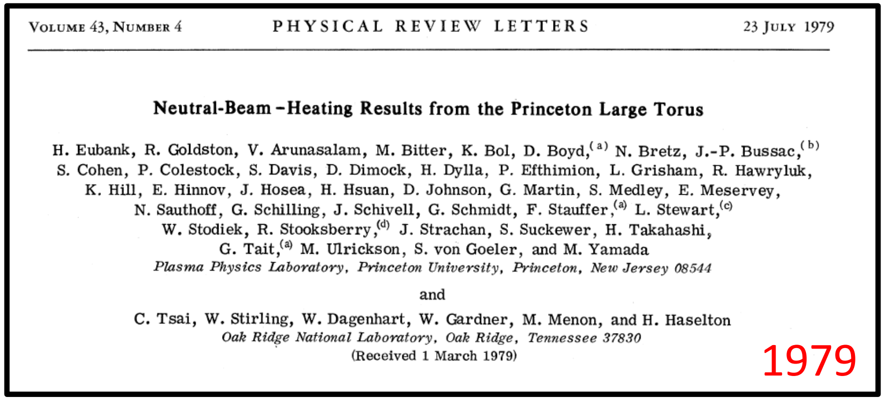


→ effect of L_n on ITG stability robust

cause:
Z_{eff} reduces the growth of the ITG instability

A new epoch: auxiliary heating

In the 70ies, start of auxiliary heating in the MW-range. Why? $\sigma_{el} \sim T_e^{3/2}$



VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Neutral-Beam–Heating Results from the Princeton Large Torus

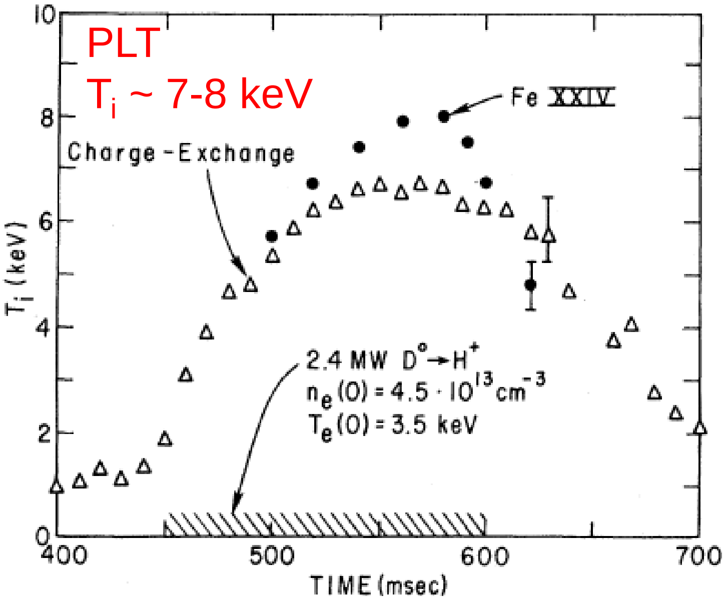
H. Eubank, R. Goldston, V. Arunasalam, M. Bitter, K. Bol, D. Boyd,(a) N. Bretz, J.-P. Bussac,(b)
S. Cohen, P. Colestock, S. Davis, D. Dimock, H. Dylla, P. Efthimion, L. Grisham, R. Hawryluk,
K. Hill, E. Hinnov, J. Hosea, H. Hsuan, D. Johnson, G. Martin, S. Medley, E. Meservey,
N. Sauthoff, G. Schilling, J. Schivell, G. Schmidt, F. Stauffer,(a) L. Stewart,(c)
W. Stodiek, R. Stooksberry,(d) J. Strachan, S. Suckewer, H. Takahashi,
G. Tait,(a) M. Ulrickson, S. von Goeler, and M. Yamada
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544

and

C. Tsai, W. Stirling, W. Dagenhart, W. Gardner, M. Menon, and H. Haselton
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 1 March 1979)

1979

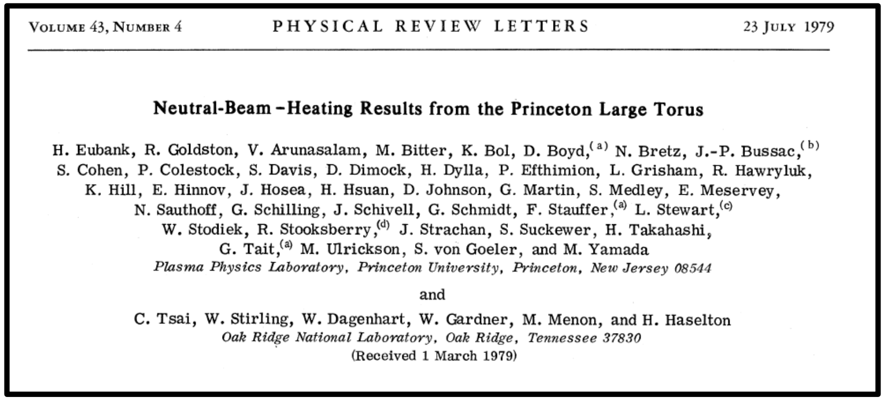


PLT

$T_i \sim$ 7-8 keV

A new epoch: auxiliary heating

In the 70ies, start of auxiliary heating in the MW-range. Why? $\sigma_{el} \sim T_e^{3/2}$



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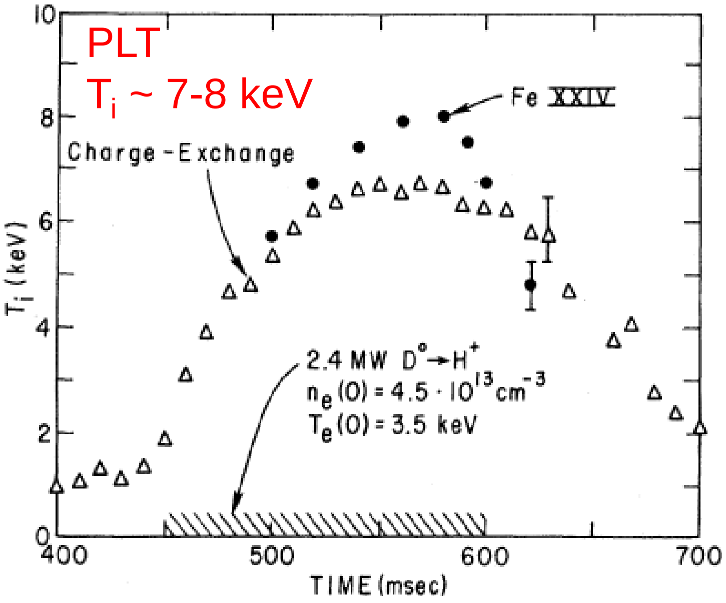
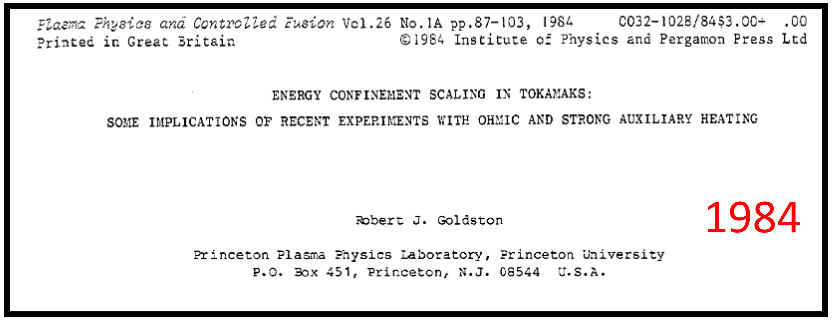


When these results were reported at the 1978 IAEA FE-conference, B. Kadomtsev praised them:

"I congratulate you (R. Goldston) and the Princeton team on the very impressive achievement of reaching high ion temperatures and penetrating far into the collisionless *region - a very important achievement for future reactor applications."*

The anti-climax: power degradation in the L-mode

beginning of the 80ies



Plasma Physics and Controlled Fusion Vol.26 No.1A pp.87-103, 1984 0032-1028/84$3.00+ .00
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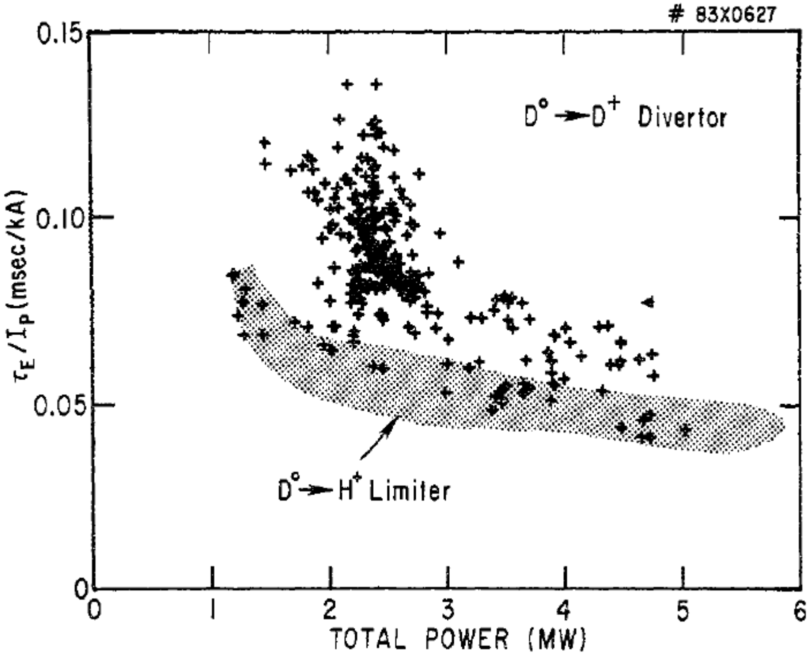
ENERGY CONFINEMENT SCALING IN TOKAMAKS:
SOME IMPLICATIONS OF RECENT EXPERIMENTS WITH OHMIC AND STRONG AUXILIARY HEATING

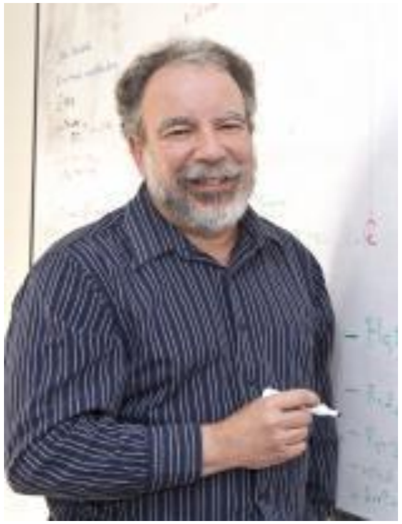
Robert J. Goldston

Princeton Plasma Physics Laboratory, Princeton University
P.O. Box 451, Princeton, N.J. 08544 U.S.A.

1984



Rob Goldston



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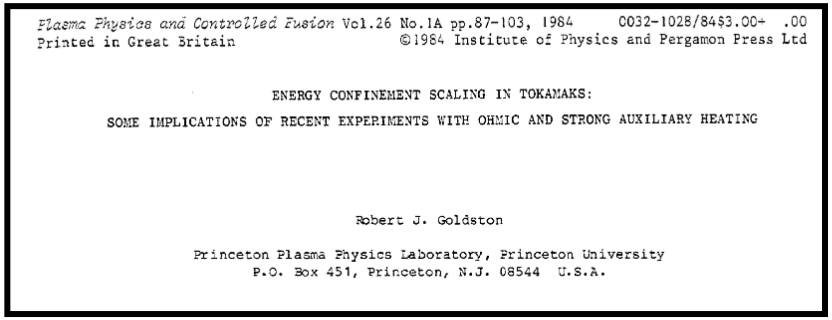

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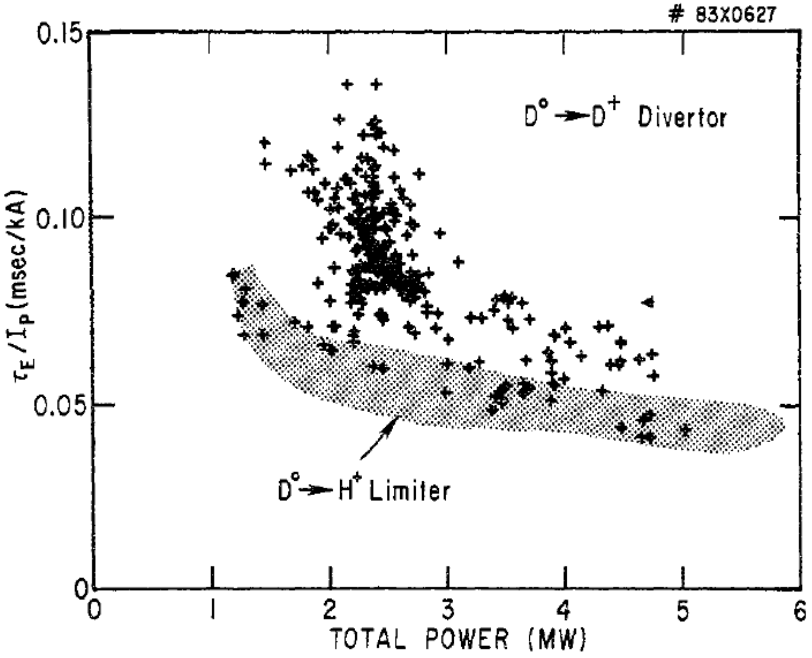
ENERGY CONFINEMENT SCALING IN TOKAMAKS:
SOME IMPLICATIONS OF RECENT EXPERIMENTS WITH OHMIC AND STRONG AUXILIARY HEATING

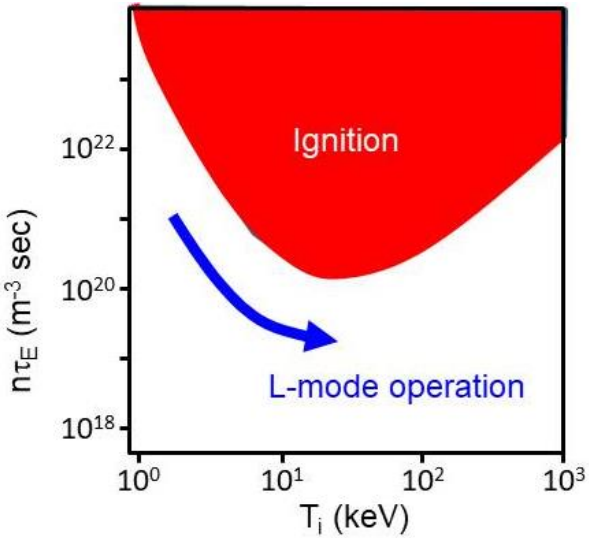
Robert J. Goldston

Princeton Plasma Physics Laboratory, Princeton University
P.O. Box 451, Princeton, N.J. 08544 U.S.A.



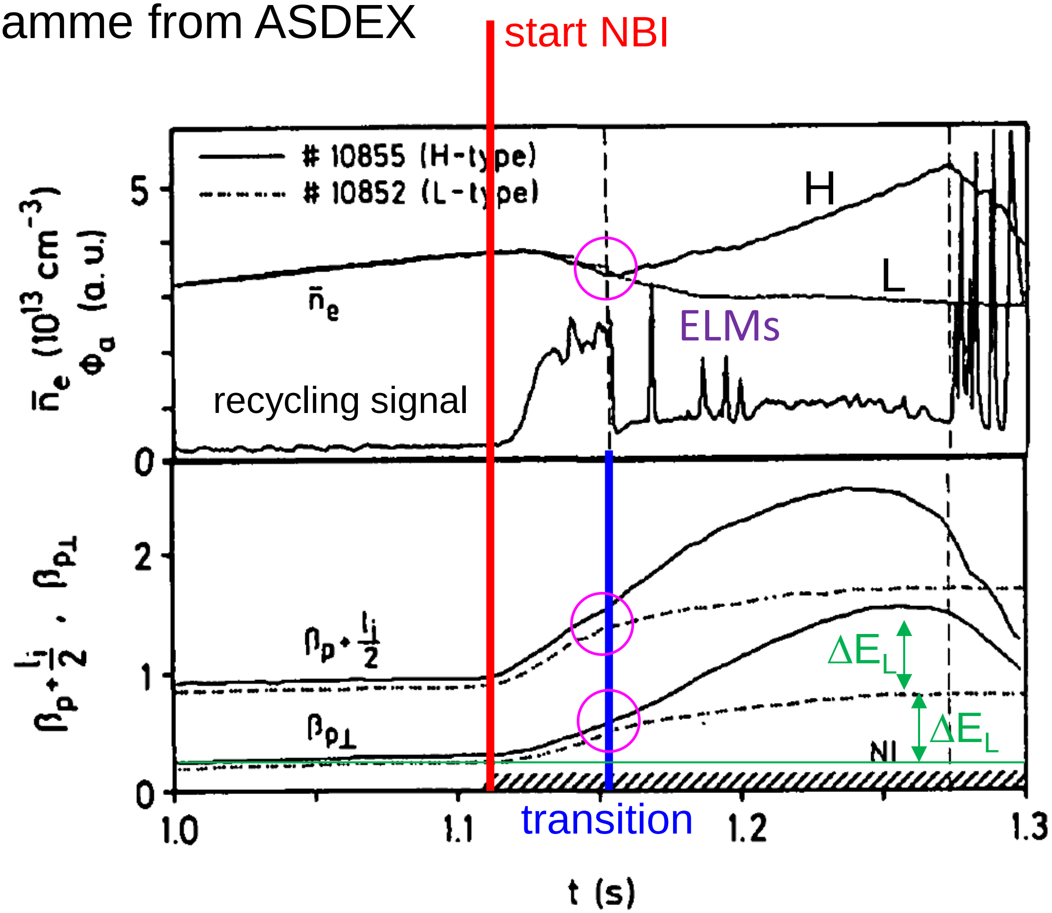
In the discussion phase of the 11th IAEA conference, P-H Rebut, then director of JET, was cited talking about a “lack of significance of auxiliary heating”

What did he mean?



The rescue (?): The H-mode of ASDEX in 1982

Historical diagramme from ASDEX



The main features of the H-mode:

- a spontaneous and distinct transition during the heating phase
- both energy- and particle confinement time increase
- a power threshold P_{thr} has to be overcome
- new instabilities appear in the H-phase: ELMs, edge-localised modes

Initial observations and relevance

(1) L- and H-modes differ in energy confinement time by about a factor of two:

energy, particle, impurity, and momentum confinement improve simultaneously;
two operational branches exist; the space in between in not accessible.

(2) The H-mode transition has a power threshold P_{thr}:

Obviously, a critical condition has to be met.

(3) There is a dwell time after the heating power has been increased from the ohmic level, before the plasma transits into the H-phase:

A formation process has been initiated by stepping up the heating power with a time scale depending on external settings.

(4) When the heating power has been switched off, the plasma remains in the H-phase again for a dwell time:

Also the back transition is not gradual but occurs in a distinct step – the gap between H- and L-mode branches.

Initial observations and relevance

(1) L- and H-modes differ in energy confinement time by about a factor of two:

energy, particle, impurity, and momentum confinement improve simultaneously;
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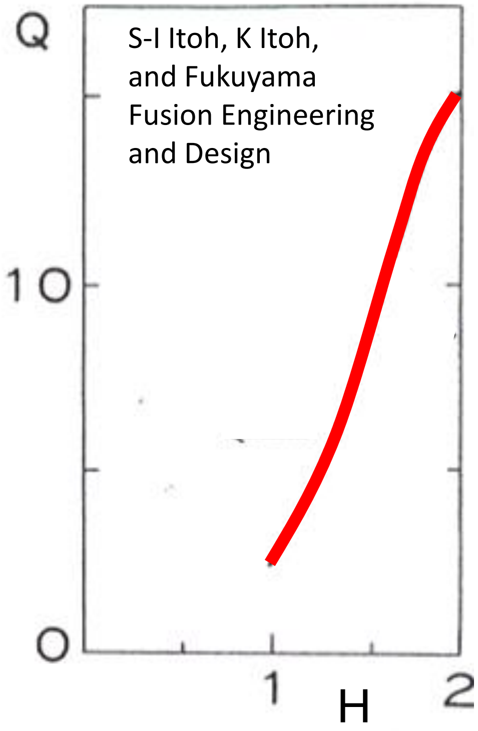
(4) When the heating power has been switched off, the plasma remains in the H-phase again for a dwell time:

Also the back transition is not gradual but occurs in a distinct step – the gap between H- and L-mode branches.

the benefit of improved confinement

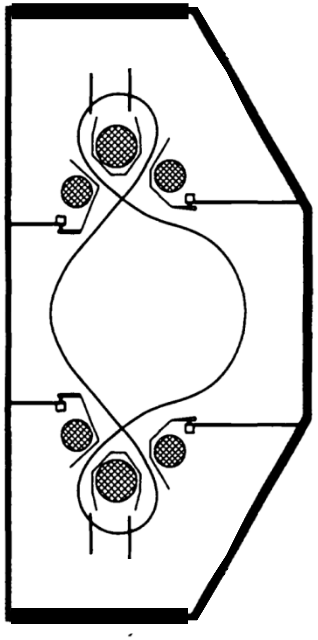


S-I Itoh, K Itoh, and Fukuyama Fusion Engineering and Design

$H = \tau_E^H / \tau_E^L$

Why was the H-mode discovered in ASDEX?

1. Divertor plasma with magnetic separatrix



2. the heating power was increased from 1.8 to 3 MW

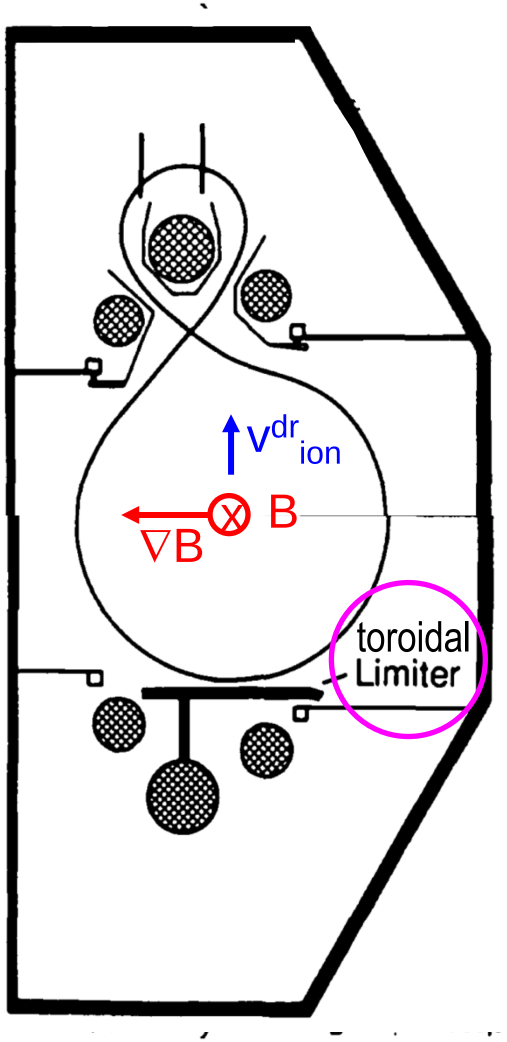
3. Operation has been restricted to upper single-null operation

A **toroidal limiter** was installed

Only upper single-null (SN) operation was possible.

Fortuitously, the Bx∇B ion drift was to the active X-point.

Thus, the power threshold was reduced



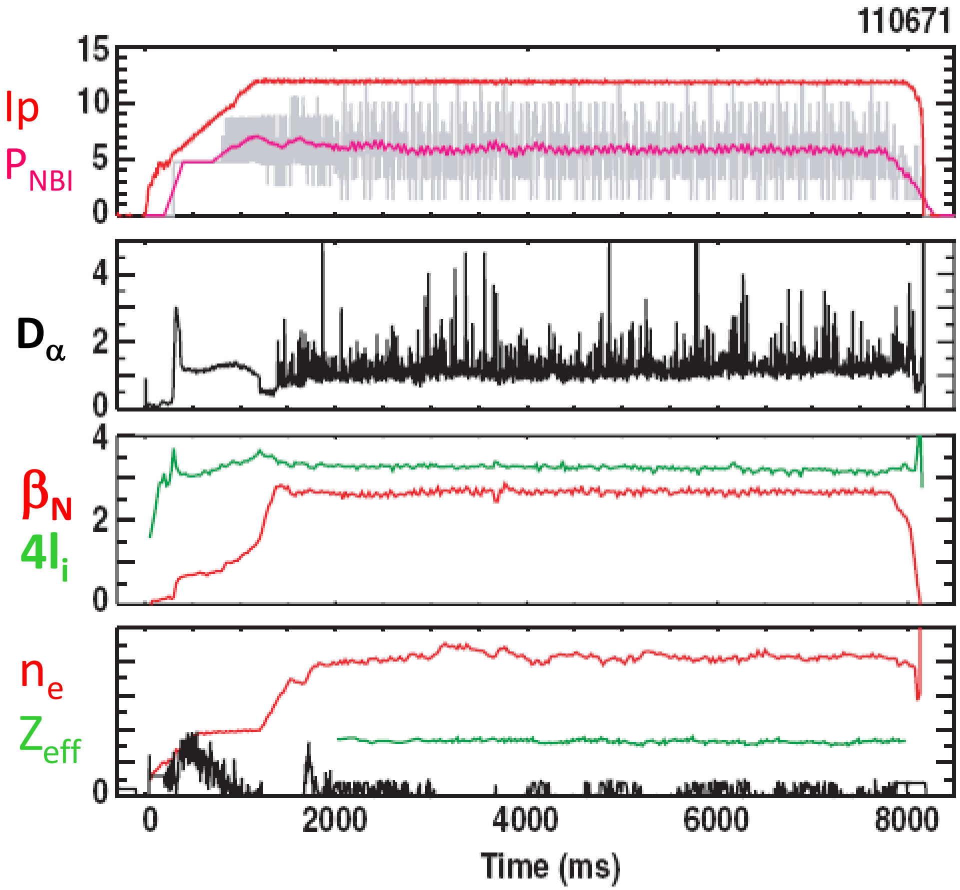
The spreading of the H-mode

Shortly after ASDEX:

PDX (1984)

then DIIID (then Doublet, 1984)

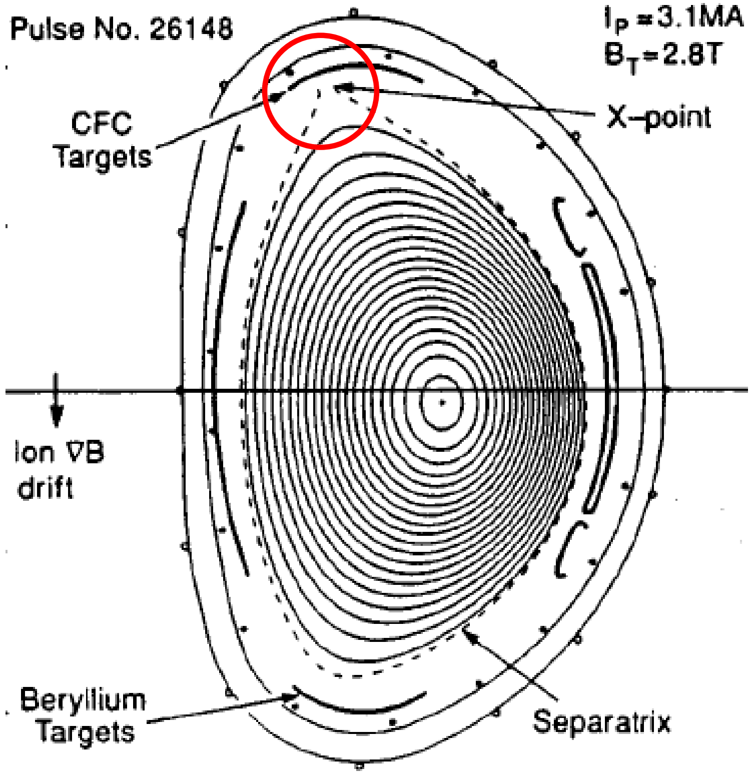
Much later:
~ 6 s high-performance H-mode discharge of DIII-D



ELMy-H-mode becomes the the basis for ITER

The special story of JET

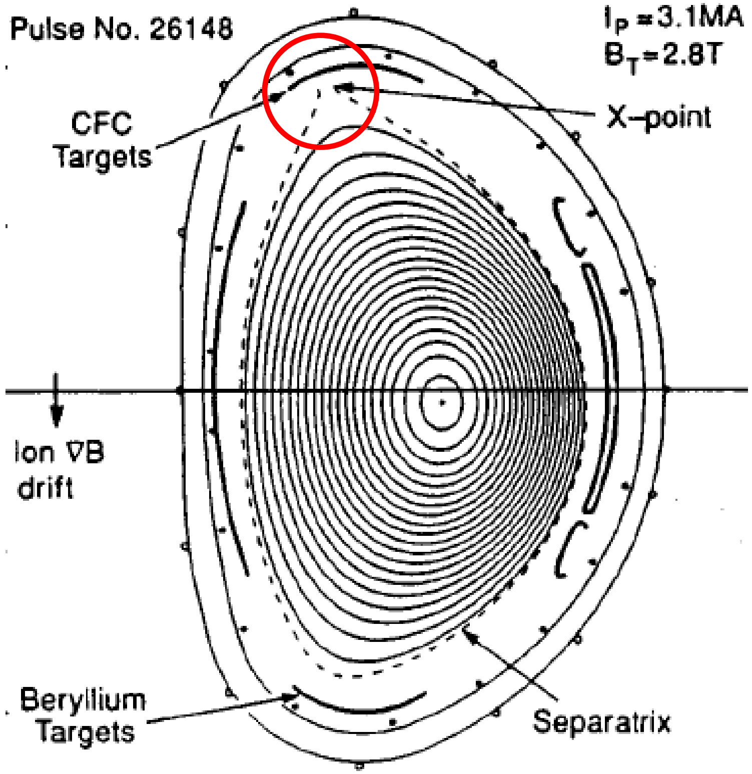
a limiter device with
marginal X-point (1985)



“ illegal” development
by late Arturo Tanga

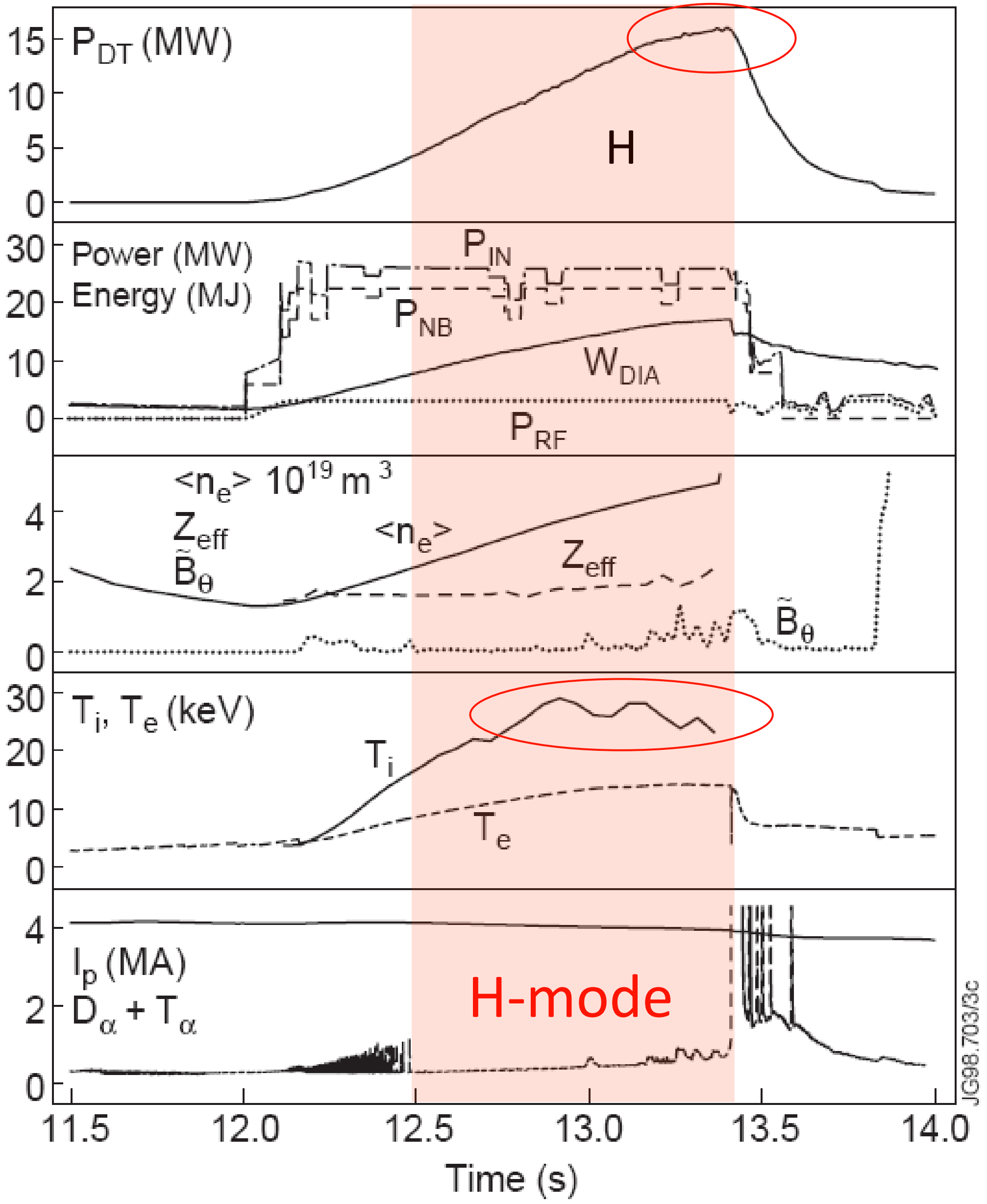
The special story of JET

a limiter device with
marginal X-point (1985)

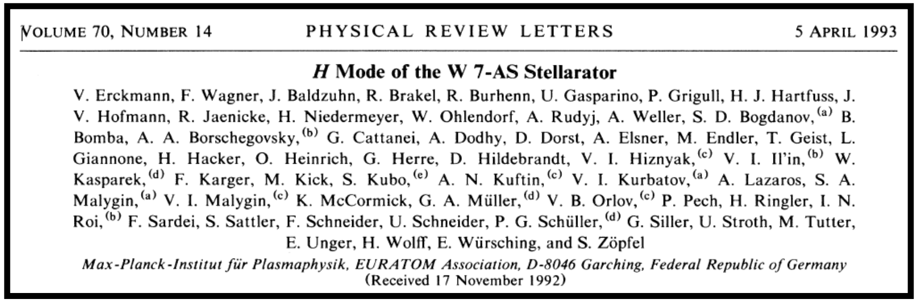


" illegal" development
by late Arturo Tanga

Much later:
The 16.1 MW DT H-mode discharge of JET



The H-mode in stellarators: 1992



VOLUME 70, NUMBER 14 PHYSICAL REVIEW LETTERS 5 APRIL 1993

***H* Mode of the W 7-AS Stellarator**

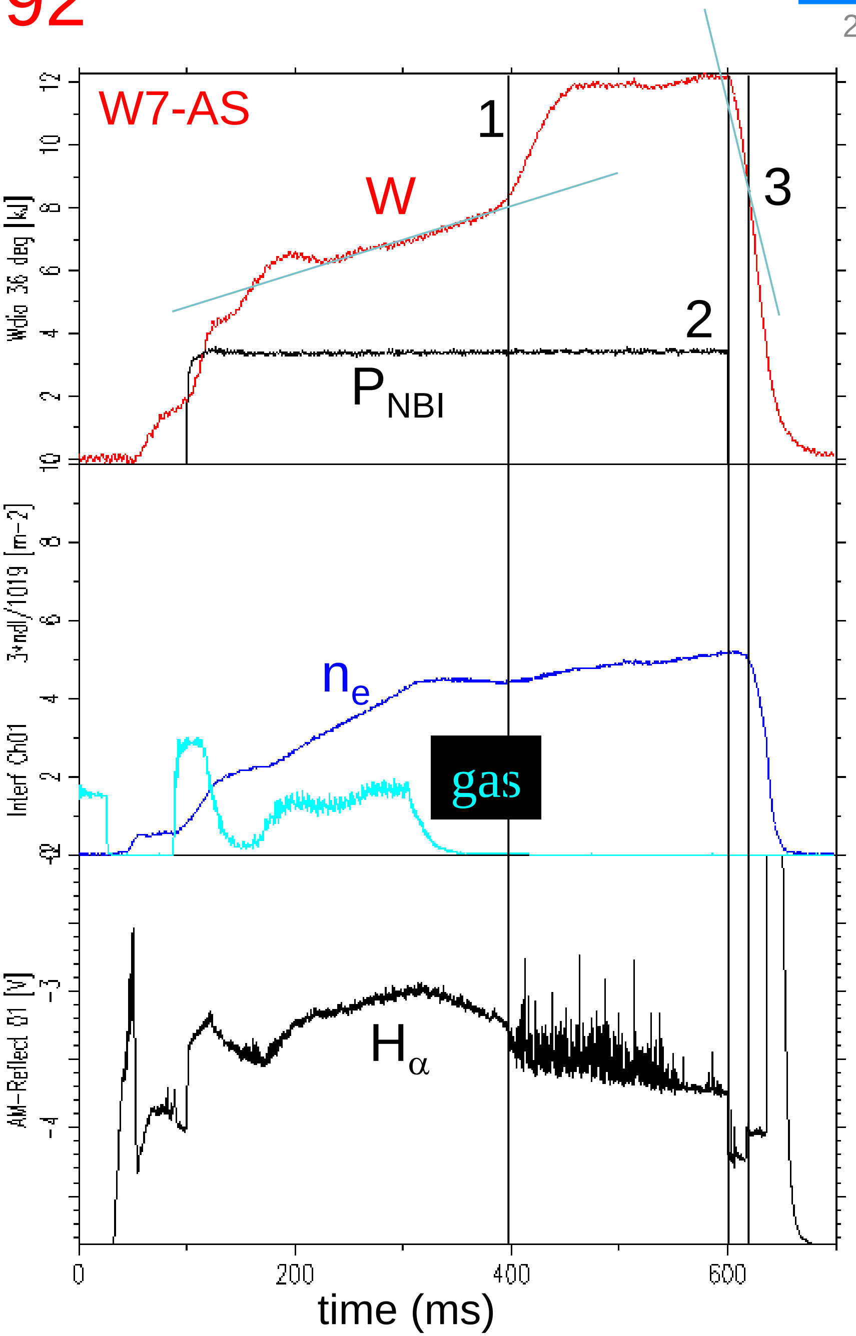
V. Erckmann, F. Wagner, J. Baldzuhn, R. Brakel, R. Burhenn, U. Gasparino, P. Grigull, H. J. Hartfuss, J. V. Hofmann, R. Jaenicke, H. Niedermeyer, W. Ohlendorf, A. Rudyj, A. Weller, S. D. Bogdanov,(a) B. Bomba, A. A. Borschegovsky,(b) G. Cattanei, A. Dodhy, D. Dorst, A. Elsner, M. Endler, T. Geist, L. Giannone, H. Hacker, O. Heinrich, G. Herre, D. Hildebrandt, V. I. Hiznyak,(c) V. I. Il'in,(b) W. Kasparek,(d) F. Karger, M. Kick, S. Kubo,(e) A. N. Kuftin,(c) V. I. Kurbatov,(a) A. Lazaros, S. A. Malygin,(a) V. I. Malygin,(c) K. McCormick, G. A. Müller,(d) V. B. Orlov,(c) P. Pech, H. Ringler, I. N. Roi,(b) F. Sardei, S. Sattler, F. Schneider, U. Schneider, P. G. Schüller,(d) G. Siller, U. Stroth, M. Tutter, E. Unger, H. Wolff, E. Würsching, and S. Zöpfel

Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-8046 Garching, Federal Republic of Germany

(Received 17 November 1992)

all main features reproduced

→ universality of the H-mode



The physics of the H-mode

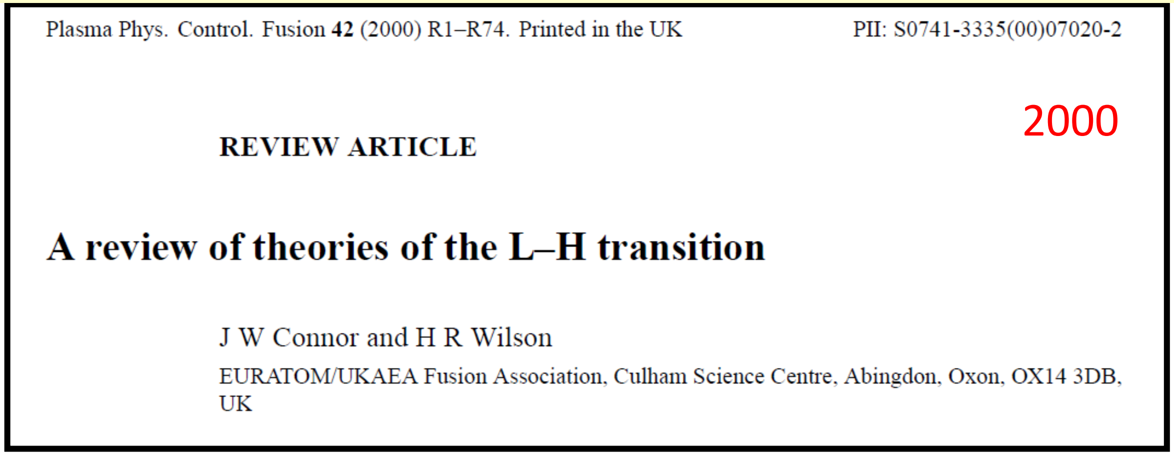
First ideas:
OH-confinement restored, but:
K. H. Burrell wrote in his 89 paper:

“At plasma currents between 2.0 and 2.5 MA, we have found that energy confinement time in H-mode can exceed the saturated Ohmic confinement time by more than a factor of two…”

K. H. Burrell et al., Plasma Phys. Control. Fusion 31 (1989) 1649.

C.M. Bishop analysed 1986 the role of the magnetic shear at the X-point on the stability of ballooning modes.
But JFT-2M produced a year later the H-mode in limiter configuration.

Many good ideas resting on “conventional” views on confinement and turbulence are summarized in the review



Plasma Phys. Control. Fusion **42** (2000) R1–R74. Printed in the UK PII: S0741-3335(00)07020-2

2000

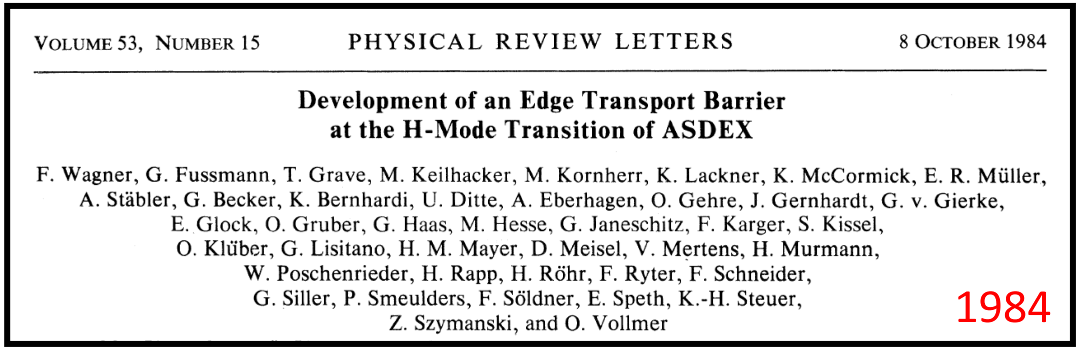
REVIEW ARTICLE

A review of theories of the L–H transition

J W Connor and H R Wilson

EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

1. step in the understanding: edge transport barrier



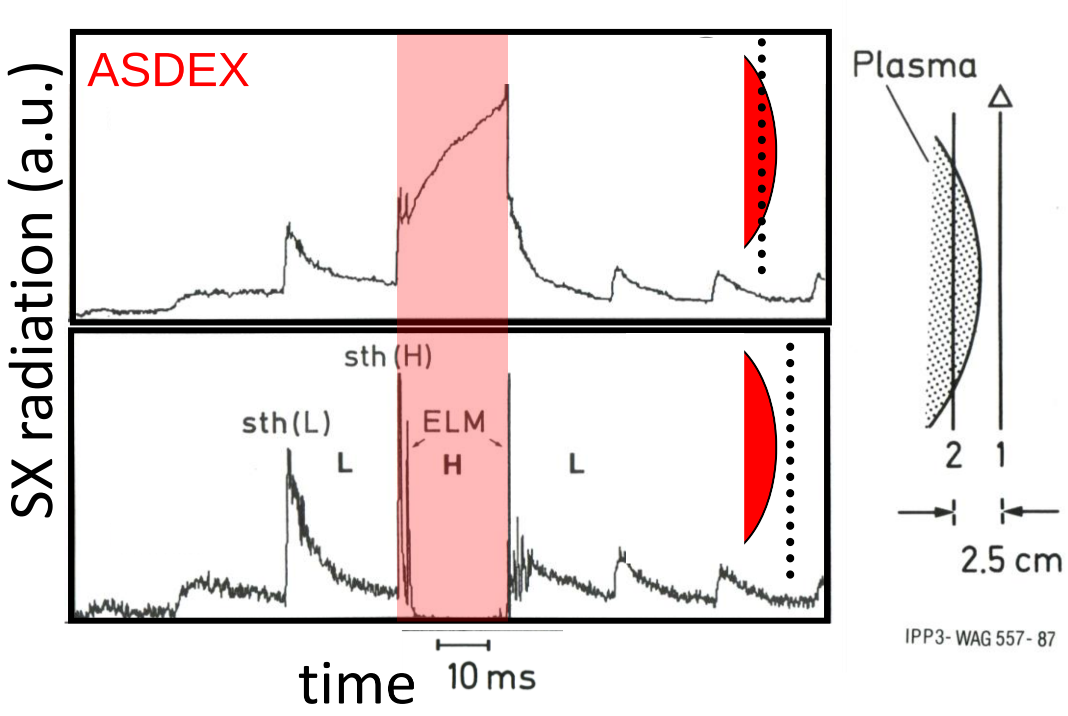
VOLUME 53, NUMBER 15 PHYSICAL REVIEW LETTERS 8 OCTOBER 1984

Development of an Edge Transport Barrier at the H-Mode Transition of ASDEX

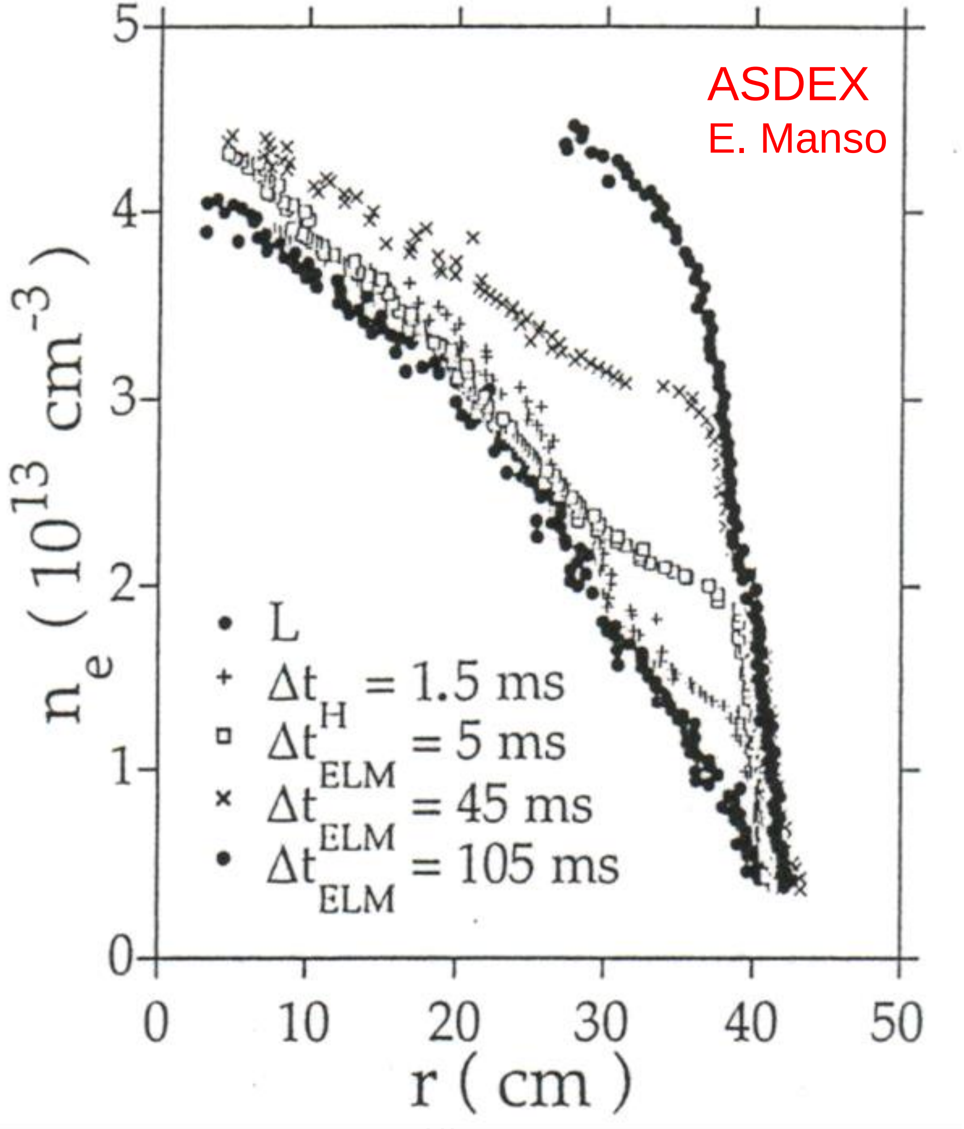
F. Wagner, G. Fussmann, T. Grave, M. Keilhacker, M. Kornherr, K. Lackner, K. McCormick, E. R. Müller, A. Stäbler, G. Becker, K. Bernhardi, U. Ditte, A. Eberhagen, O. Gehre, J. Gernhardt, G. v. Gierke, E. Glock, O. Gruber, G. Haas, M. Hesse, G. Janeschitz, F. Karger, S. Kissel, O. Klüber, G. Lisitano, H. M. Mayer, D. Meisel, V. Mertens, H. Murmann, W. Poschenrieder, H. Rapp, H. Röhr, F. Ryter, F. Schneider, G. Siller, P. Smeulders, F. Söldner, E. Speth, K.-H. Steuer, Z. Szymanski, and O. Vollmer

1984

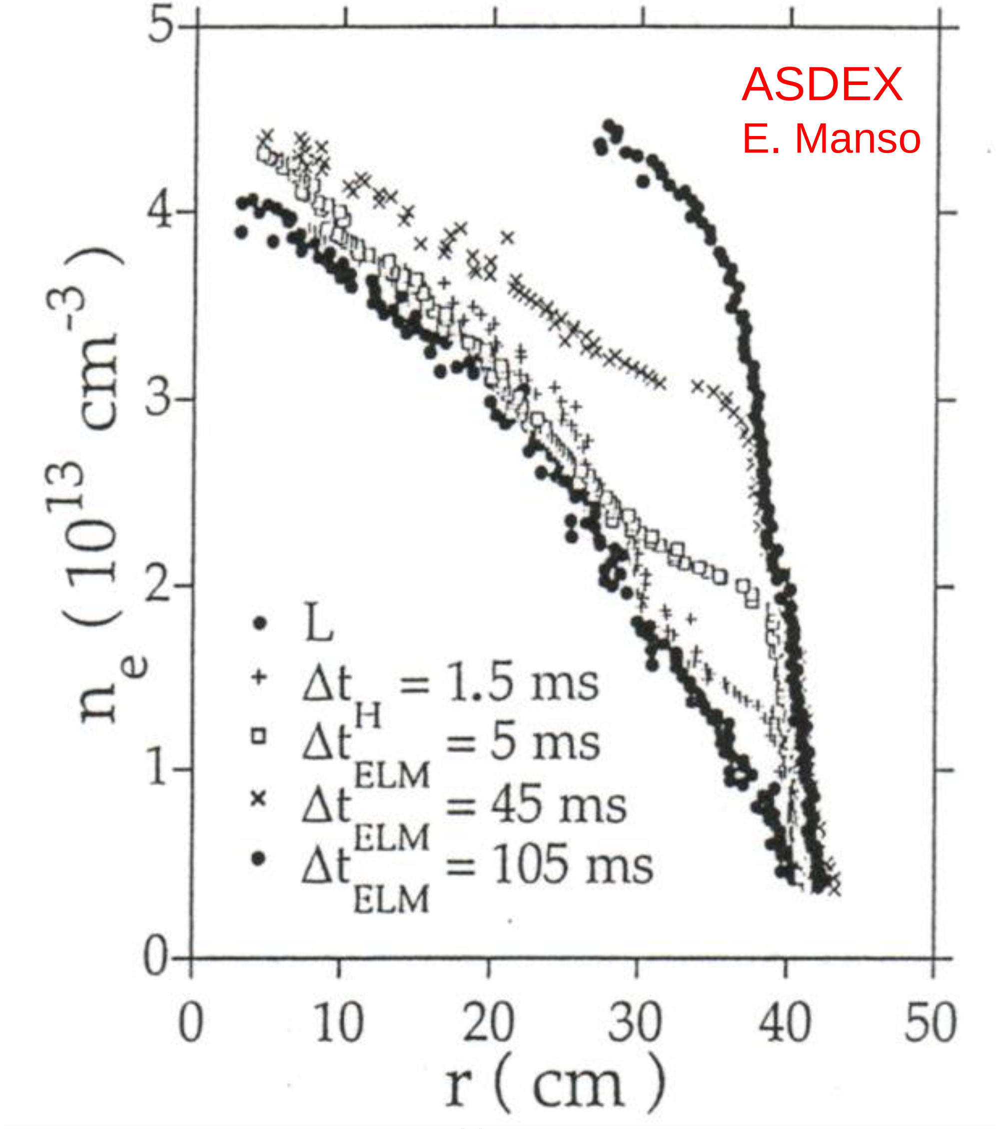
Modulation of SX radiation at edge and in SOL via sawteeth



H-mode feature: edge pedestals

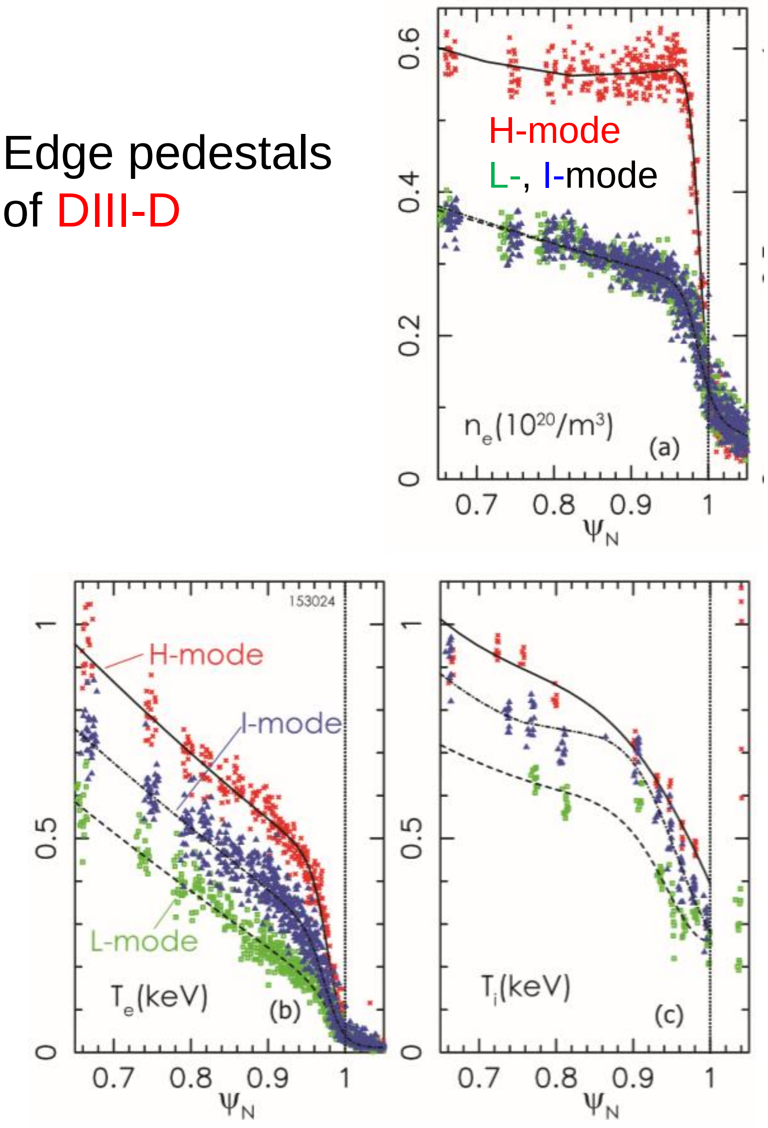


H-mode feature: edge pedestals



ASDEX
E. Manso

Edge pedestals
of DIII-D



A. Hubbard et al., NF 56, 086003, 2016

When you google “edge pedestal and H-mode”

2^{nd} step: E_r enters magnetic confinement

E_r is an implicit parameter in tokamak transport: $\Gamma_e=\Gamma_i$ at continuous symmetry

First mention of E_r at the IAEA FE conference in 1984.

R. J. Taylor asks M. Keilhacker after his JET-talk:

"*Now, if it is a radial barrier, is it related to the radial electric field?*"

Stellarators are not continuously symmetric: An ambi-polar electric field enforces $\Gamma_e=\Gamma_i$
E_r plays an **explicit** role; development of roots (electron-, ion-root)

E_r was introduced into H-mode theory by "stellarator people " S.I. Itoh, K. Itoh and K.C. Shaing in 1989.

K.C.
Shaing

2^{nd} step: E_r enters magnetic confinement

E_r not an explicit parameter in tokamak transport: $\Gamma_e=\Gamma_i$ at continuous symmetry

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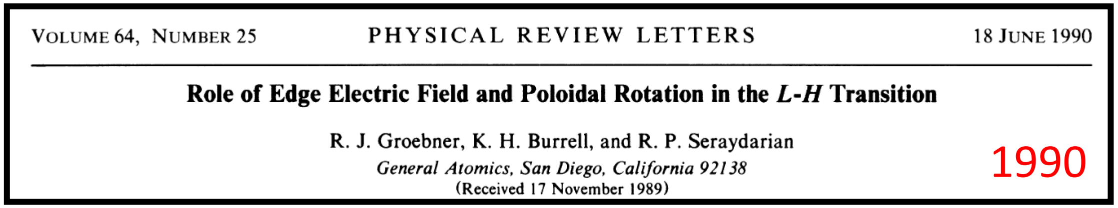
K.C.
Shaing

J. W. Connor and H. R. Wilson wrote in their 2000 NF paper:

A review of theories of the L-H transition

"Remarkably, changes in E_r at the transition were predicted theoretically (…) before they were observed experimentally; the observation of these has led to their inclusion in many later theories."

3. Step: The pioneering achievements of DIII-D



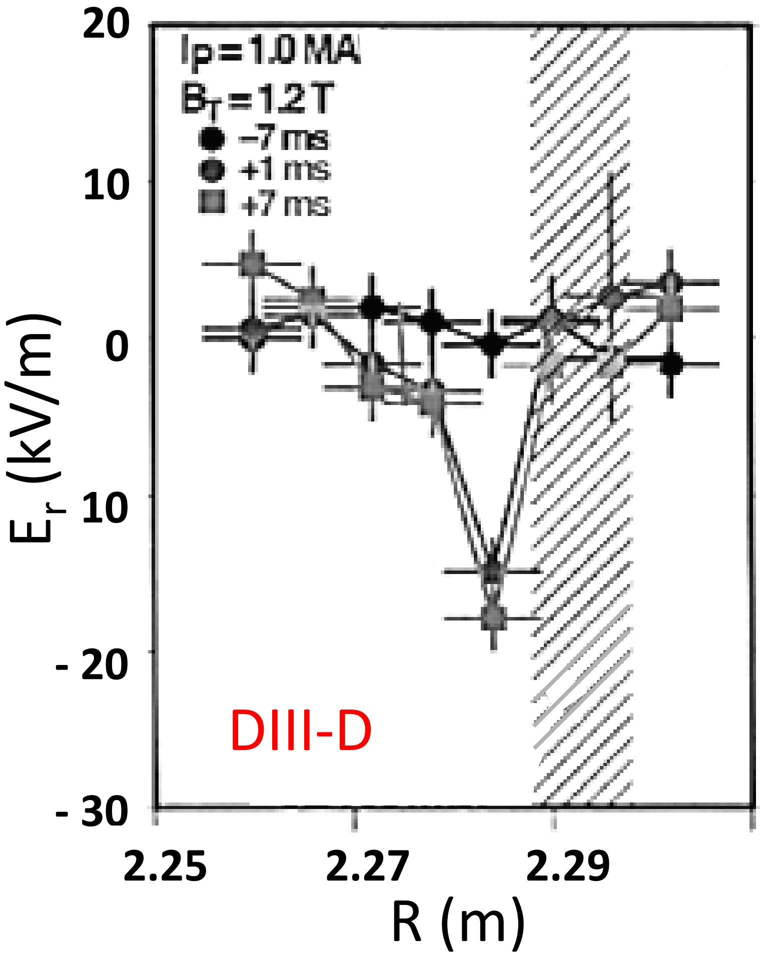
VOLUME 64, NUMBER 25 PHYSICAL REVIEW LETTERS 18 JUNE 1990

Role of Edge Electric Field and Poloidal Rotation in the *L*-*H* Transition

R. J. Groebner, K. H. Burrell, and R. P. Seraydarian
General Atomics, San Diego, California 92138

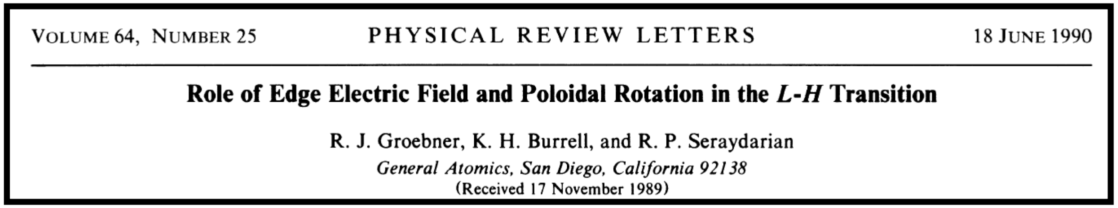
(Received 17 November 1989)

1990



First documentation of strong E_r change at the plasma edge

The strong effect of the H-transition on E_r(edge)



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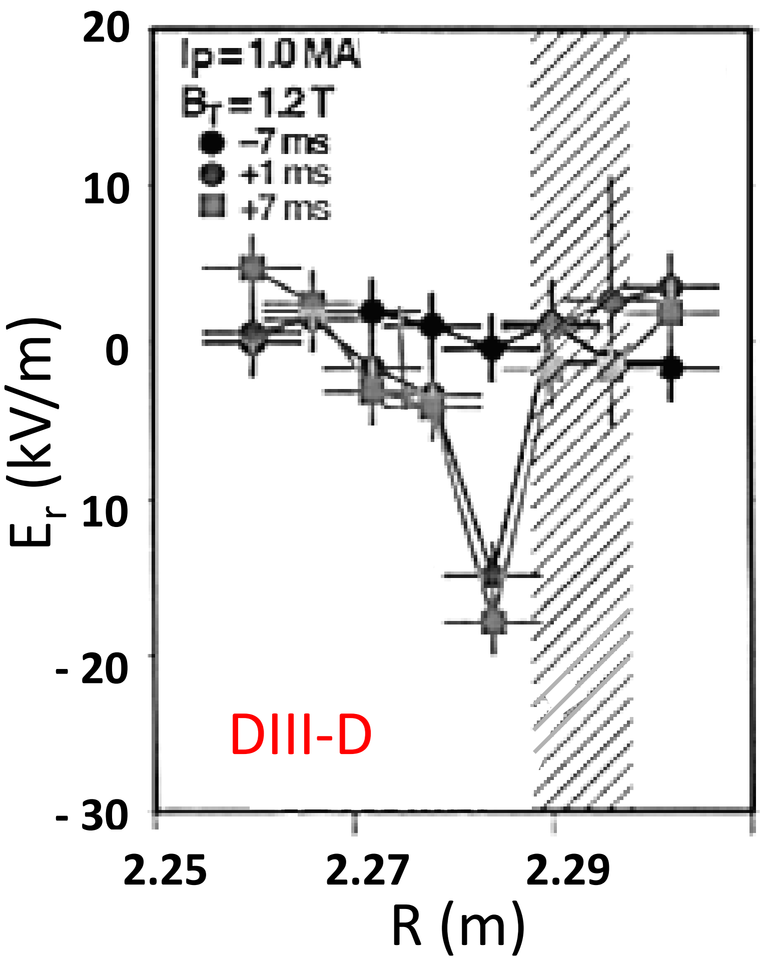
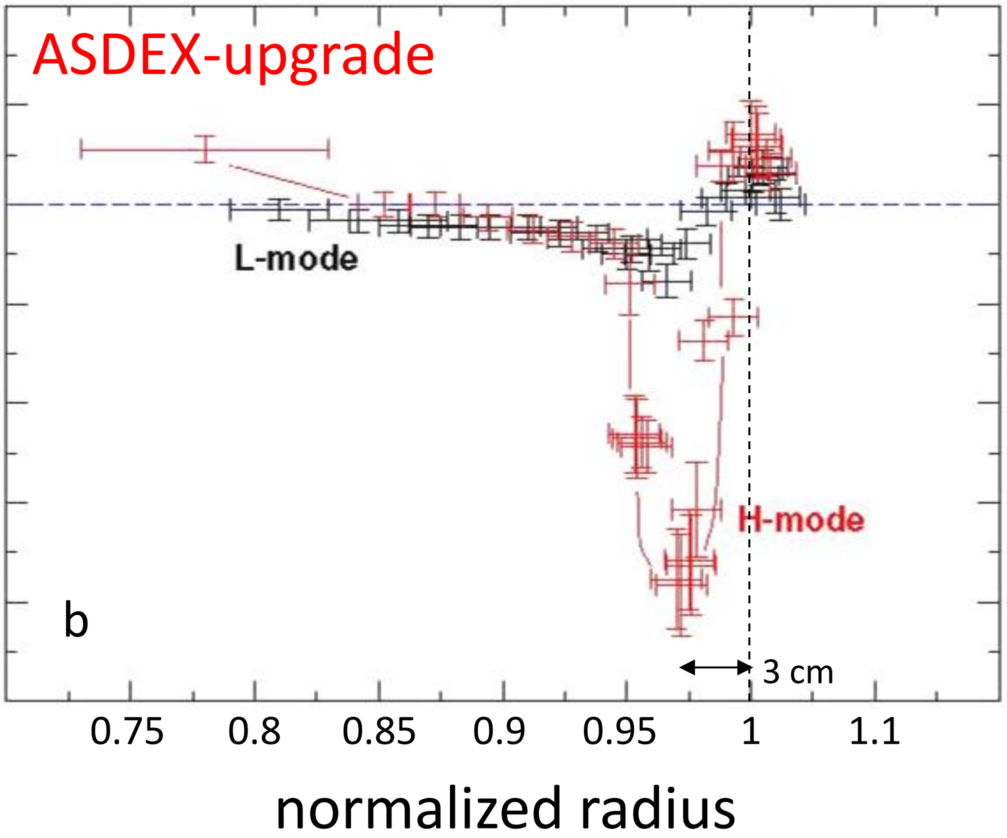


Nowadays with improved diagnostics



Quiescent nature of the edge transport barrier

reduction of turbulence
within transport barrier

reduction of the edge transport
measured with Langmuir probes

ASDEX 1988

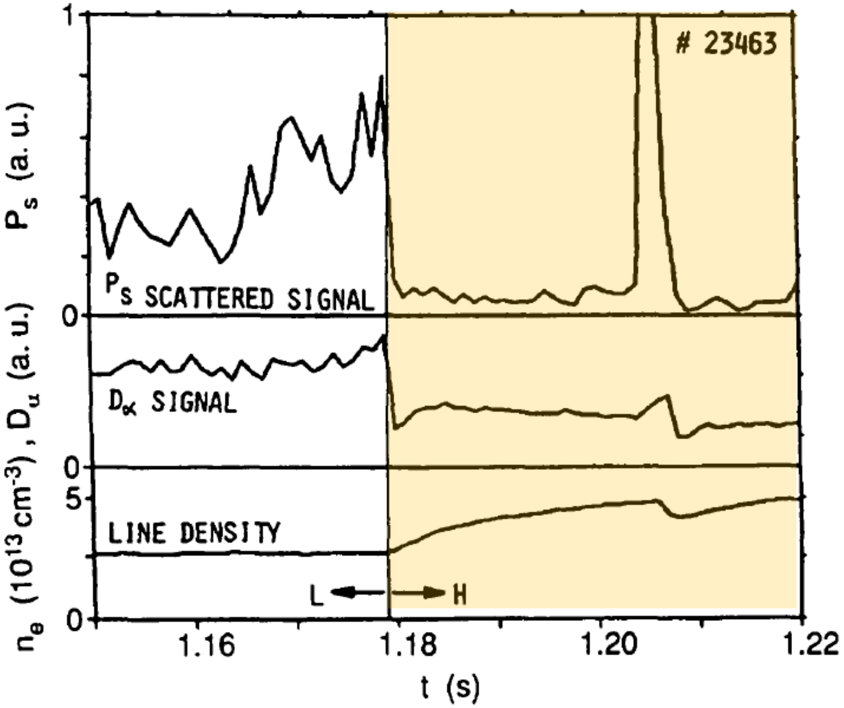
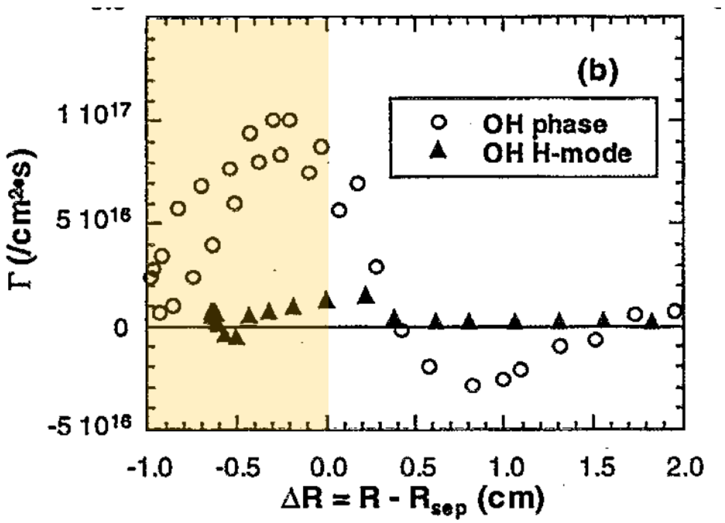


FIG. 80. Scattered signal power P_s measured close to the separatrix at the transition from an L-phase to a quiescent H-phase at $k_\perp = 3$ cm^{-1} (outer vertical chord). Also plotted are the D_α signal in the divertor and the electron line density 30 cm from the plasma centre.

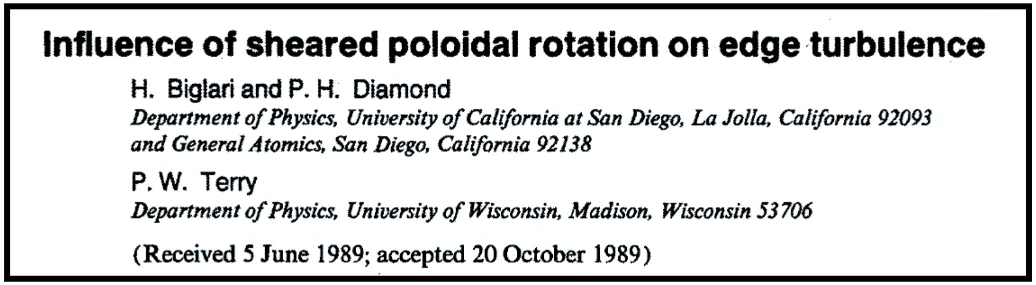
DIII-D 1995



Within the edge barrier:
fluctuations and particle flux are strongly reduced

whereas the gradients steepen

4. Step - The BDT criterion, 1989

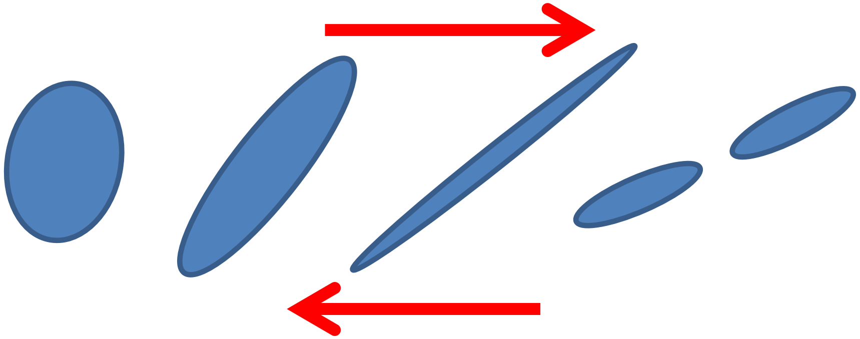


Influence of sheared poloidal rotation on edge turbulence

H. Biglari and P. H. Diamond
Department of Physics, University of California at San Diego, La Jolla, California 92093 and General Atomics, San Diego, California 92138
P. W. Terry
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

(Received 5 June 1989; accepted 20 October 1989)

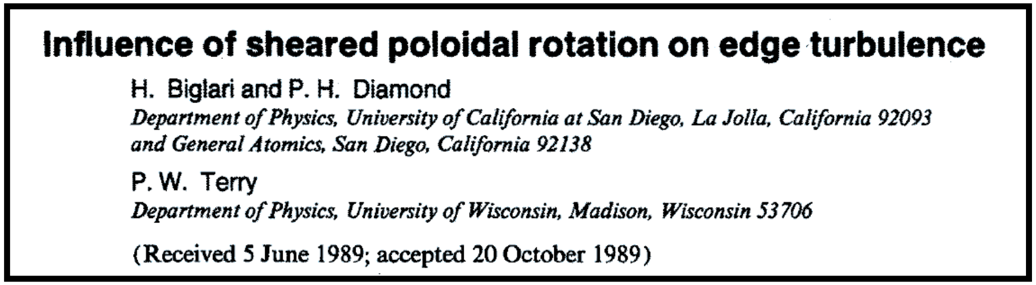
Basic idea:
In a magnetised plasma E_r and ExB flow are equivalent
The perpendicular flow is inhomogeneous, it has shear
The following process happens:



Turbulent eddies are tilted, stretched and strained out.

The turbulence structures are **decorrelated** leading to a lower turbulence level and reduced transport

4. Step - The BDT criterion, 1989



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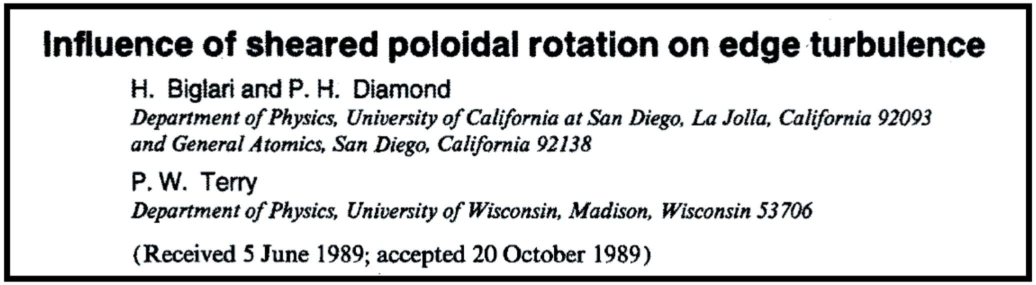
Quantitatively:

The shearing rate > turbulence growth rate: $\omega_{ExB} > \gamma_{lin}^{max}$

$$\omega_{E\times B} \approx \frac{1}{B_{tor}} \frac{\partial E_r}{\partial r}$$

$$\gamma_{lin}^{max} \sim \frac{v_T}{L_T} \qquad v_T = \sqrt{\frac{2T}{m}} \qquad L_T = \frac{T}{\nabla T}$$

4. Step - The BDT criterion, 1989



Influence of sheared poloidal rotation on edge turbulence

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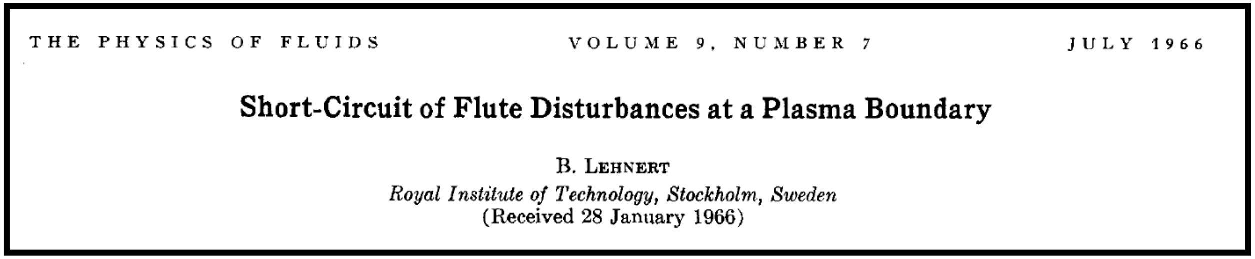
Bo Lehnert

Historical reminiscence, 1966:



THE PHYSICS OF FLUIDS VOLUME 9, NUMBER 7 JULY 1966

Short-Circuit of Flute Disturbances at a Plasma Boundary

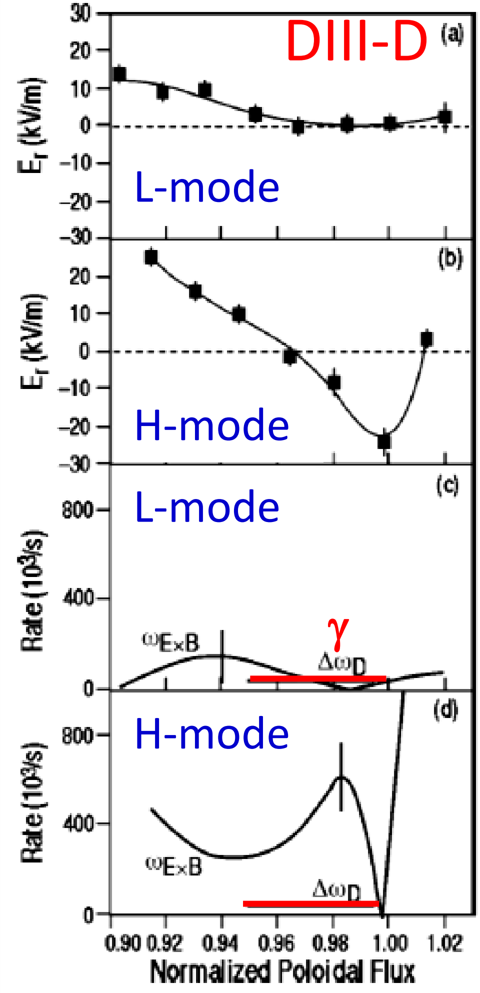
B. Lehnert
Royal Institute of Technology, Stockholm, Sweden

(Received 28 January 1966)

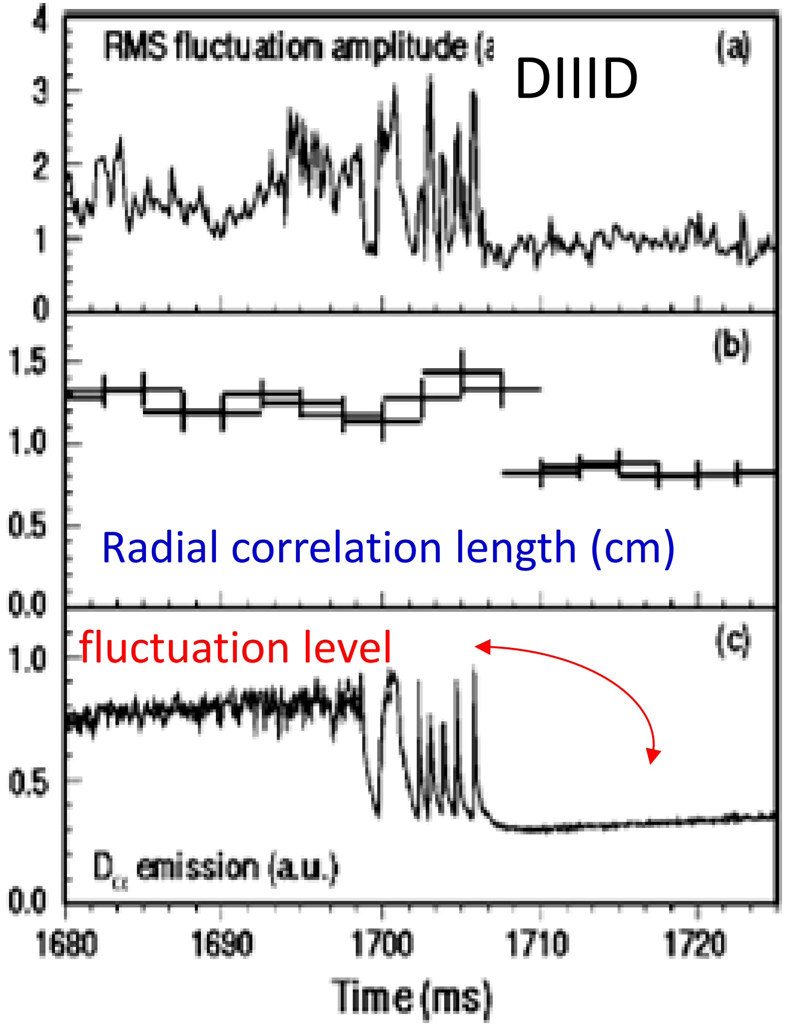
“Thus, a non-uniform velocity should have a stabilizing tendency by “smearing out” the flute disturbance.”

5. Step: Confirmation of the BDT criterion by DIII-D

Conditions for flow-decorrelation



Reduction of radial correlation lenth



BUT: What is the origin of E_r?

The radial force balance enters: $E_r = \frac{1}{Z_i\, e\, ni} \frac{\partial pi}{\partial r} + v_\Phi B_\theta - v_\theta B_\Phi$

energy balance with anomalous transport at the edge

momentum input and transport

poloidal force balance

Poloidal force balance: $0 = j_r B/n - m_i \mu_\theta v_\theta + m_i \vartheta/\vartheta r\, (<\tilde{v}_r \tilde{v}_\theta>)$

ion-losses
momentum losses
into SOL

polarisation experiments

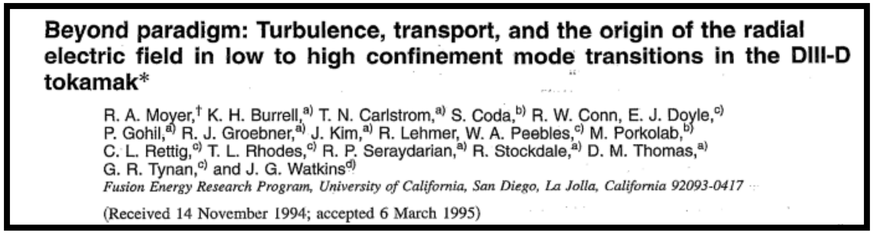
neo-classical damping

specific for stellarators

turbulent Reynolds stress

2D: spectral transport from small to large scales
→ zonal flows

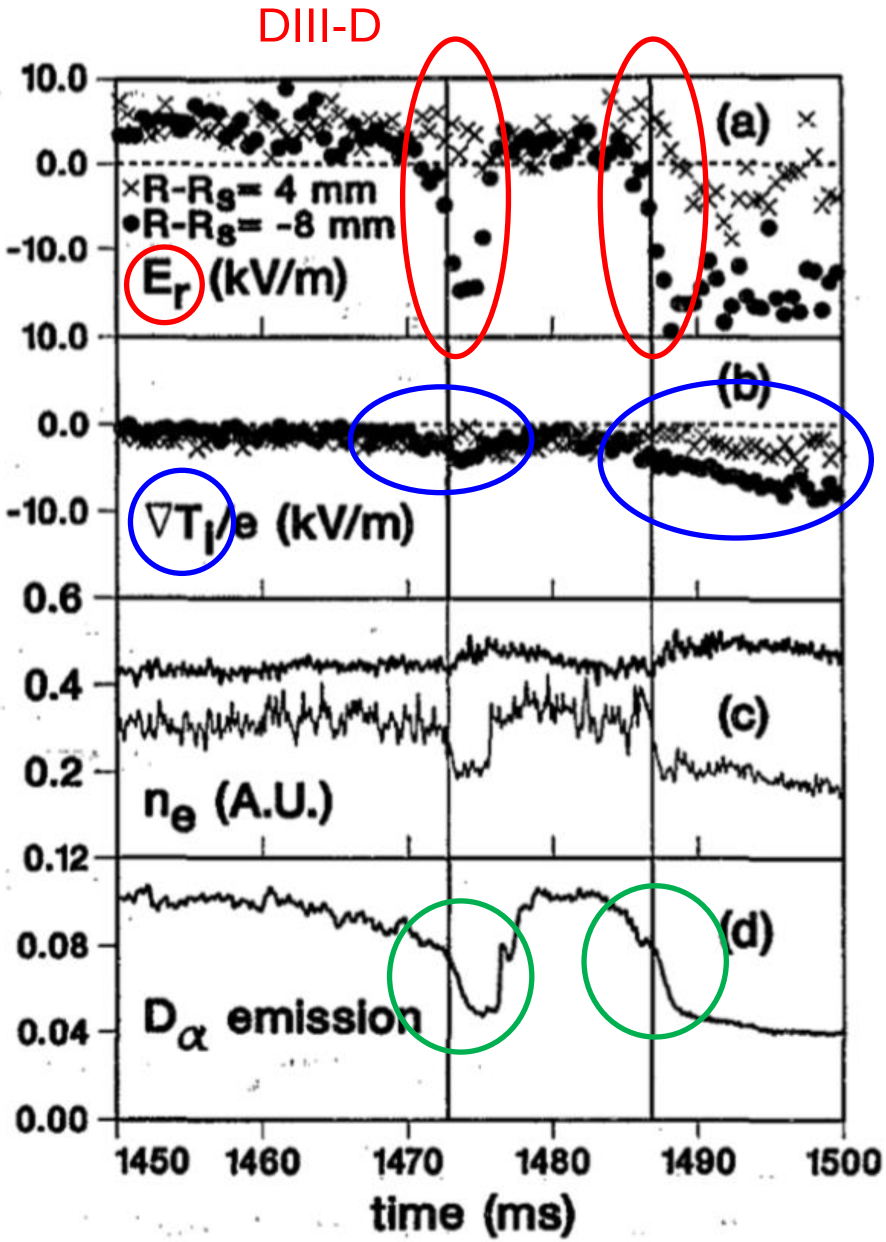
Evidence for the vxB-term: 1994



Beyond paradigm: Turbulence, transport, and the origin of the radial electric field in low to high confinement mode transitions in the DIII-D tokamak*

R. A. Moyer,† K. H. Burrell,[a] T. N. Carlstrom,[a] S. Coda,[b] R. W. Conn, E. J. Doyle,[c] P. Gohil,[a] R. J. Groebner,[a] J. Kim,[a] R. Lehmer, W. A. Peebles,[c] M. Porkolab,[b] C. L. Rettig,[c] T. L. Rhodes,[c] R. P. Seraydarian,[a] R. Stockdale,[a] D. M. Thomas,[a] G. R. Tynan,[c] and J. G. Watkins[d]
Fusion Energy Research Program, University of California, San Diego, La Jolla, California 92093-0417

(Received 14 November 1994; accepted 6 March 1995)

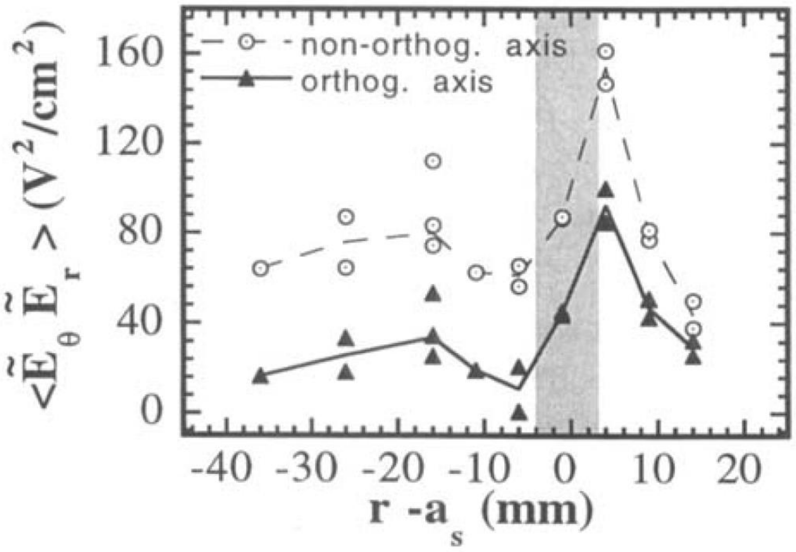


E$_r$ changes faster
than
∇p$_i$ at the edge

Evidence for Reynolds stress

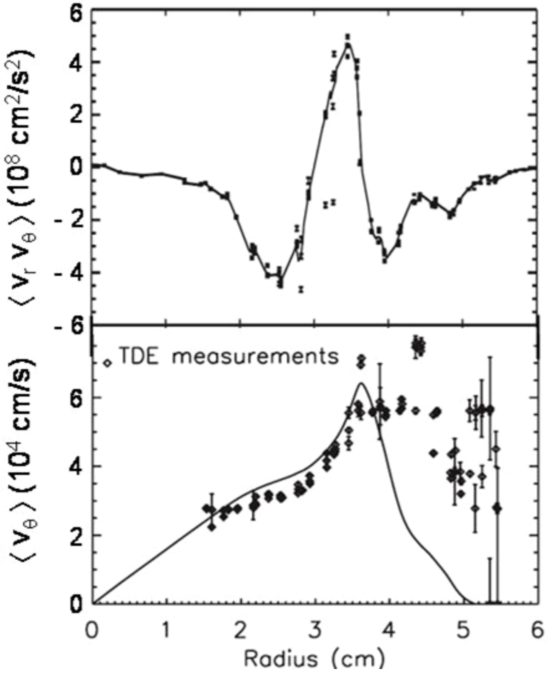
Reynolds stress
in the shear layer of TJ-II
C. Hidalgo et al.

2000



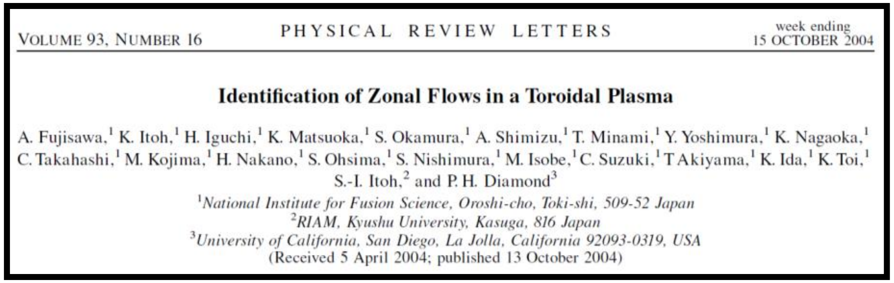
Reynolds stress
leads to st.st. flow
and E_r
C. Holland et al.

CSDX
2006



Status now: turbulence causes Reynolds stress
causing ExB flow in the form of zonal flows
which acts back on and regulates the level of turbulence

Induced flows in two forms: ZFs and GAMs



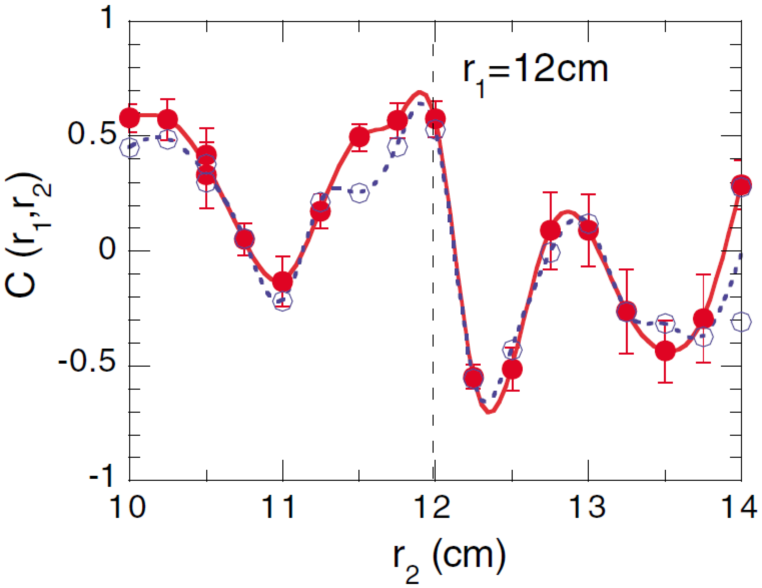
VOLUME 93, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2004

Identification of Zonal Flows in a Toroidal Plasma

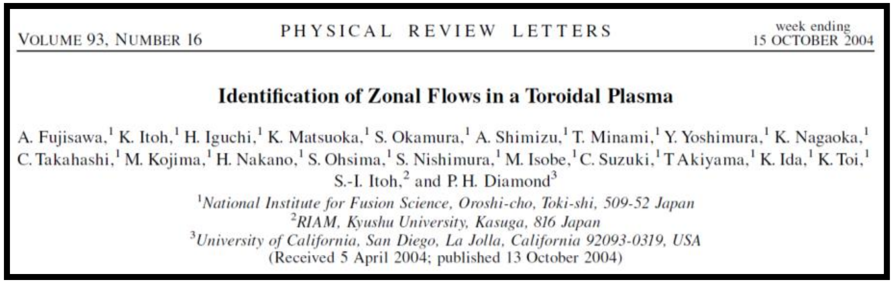
A. Fujisawa,[1] K. Itoh,[1] H. Iguchi,[1] K. Matsuoka,[1] S. Okamura,[1] A. Shimizu,[1] T. Minami,[1] Y. Yoshimura,[1] K. Nagaoka,[1] C. Takahashi,[1] M. Kojima,[1] H. Nakano,[1] S. Ohsima,[1] S. Nishimura,[1] M. Isobe,[1] C. Suzuki,[1] T Akiyama,[1] K. Ida,[1] K. Toi,[1] S.-I. Itoh,[2] and P. H. Diamond[3]
[1] *National Institute for Fusion Science, Oroshi-cho, Toki-shi, 509-52 Japan*
[2] *RIAM, Kyushu University, Kasuga, 816 Japan*
[3] *University of California, San Diego, La Jolla, California 92093-0319, USA*

(Received 5 April 2004; published 13 October 2004)

Radial structure of a zonal flow, CHS 2004



Induced flows in two forms: ZFs and GAMs



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[1]*National Institute for Fusion Science, Oroshi-cho, Toki-shi, 509-52 Japan*
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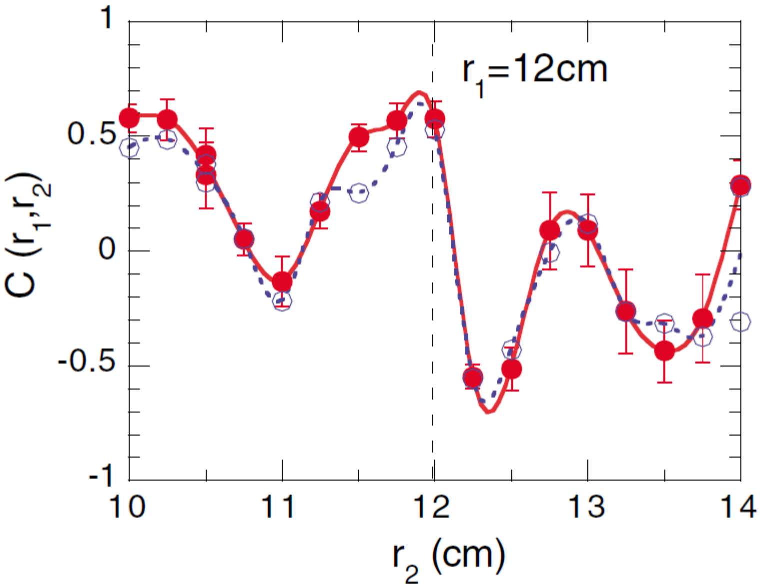
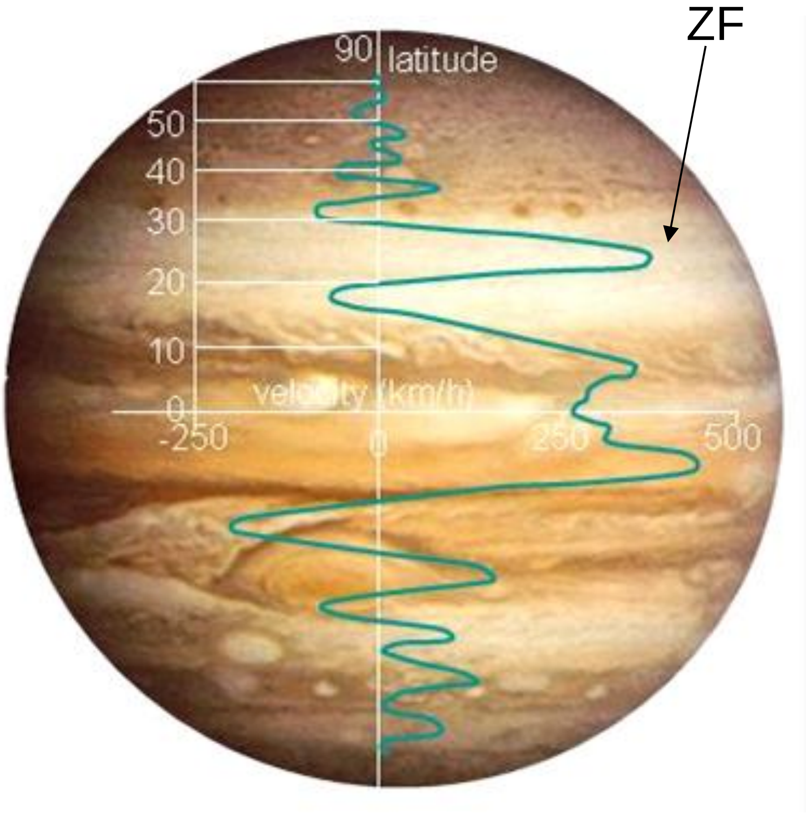


The beauty of this physics
Planet Jupiter

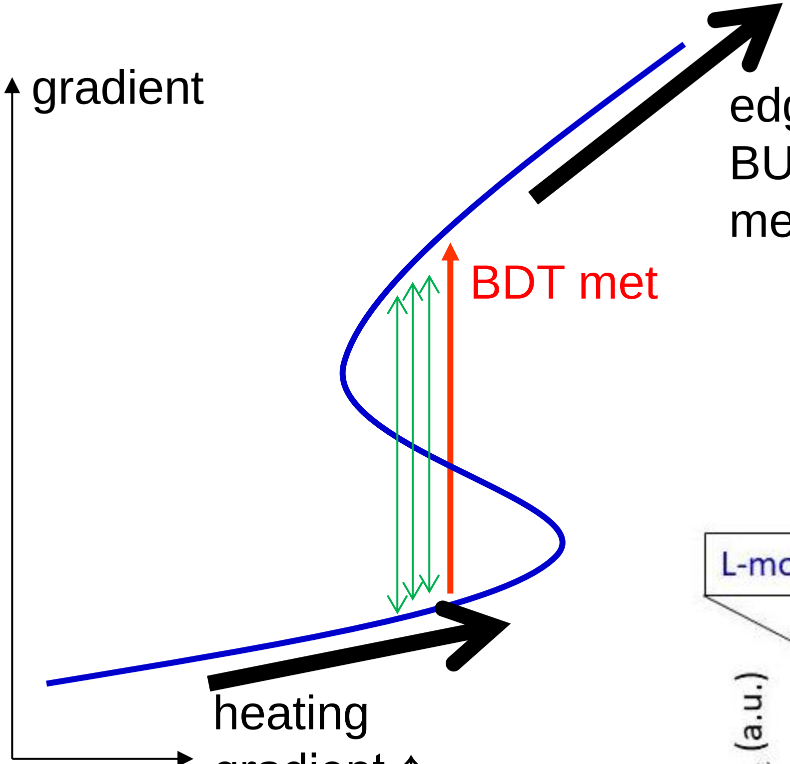


Visualisation of spectral transport in 2D turbulence

2D model system using an electrolyte and jxB forces to drive eddies

A. Shats, ANU, Canberra

General concept: The L-H transition as a bifurcation

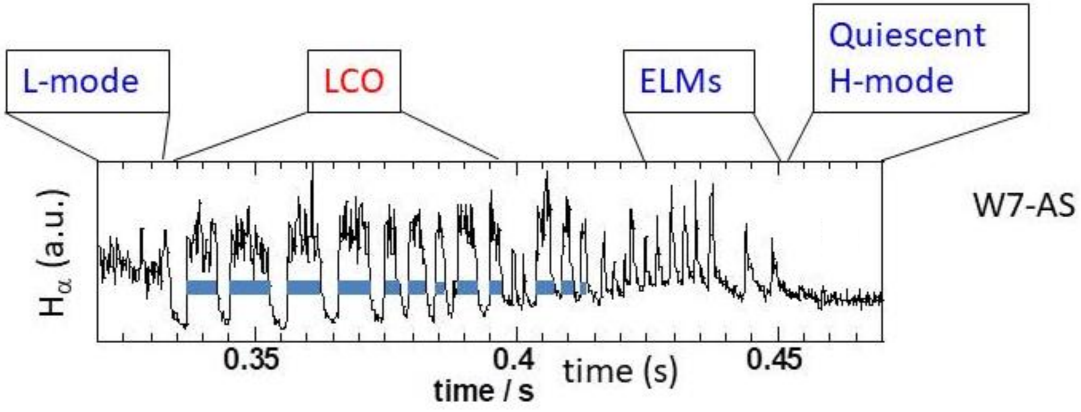


edge fluctuations gone, RS gone
BUT: ∇p_i large
mean ExB flow maintains BDT

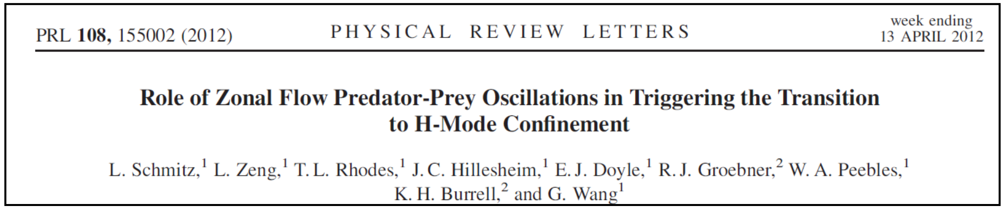
flux

heating
gradient ↑
turbulence level ↑
∇p_i, RS ↑

at transition:
limit cycle oscillations



Formal treatment of L-H transition: predator-prey complex



PRL **108,** 155002 (2012) PHYSICAL REVIEW LETTERS week ending 13 APRIL 2012

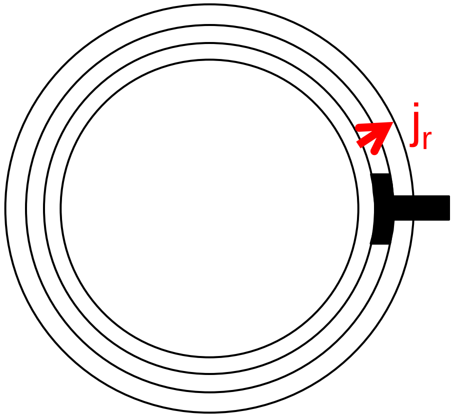
Role of Zonal Flow Predator-Prey Oscillations in Triggering the Transition to H-Mode Confinement

L. Schmitz,[1] L. Zeng,[1] T. L. Rhodes,[1] J. C. Hillesheim,[1] E. J. Doyle,[1] R. J. Groebner,[2] W. A. Peebles,[1] K. H. Burrell,[2] and G. Wang[1]

2012

The causality chain: induced H-mode of TEXTOR

plasma
biasing

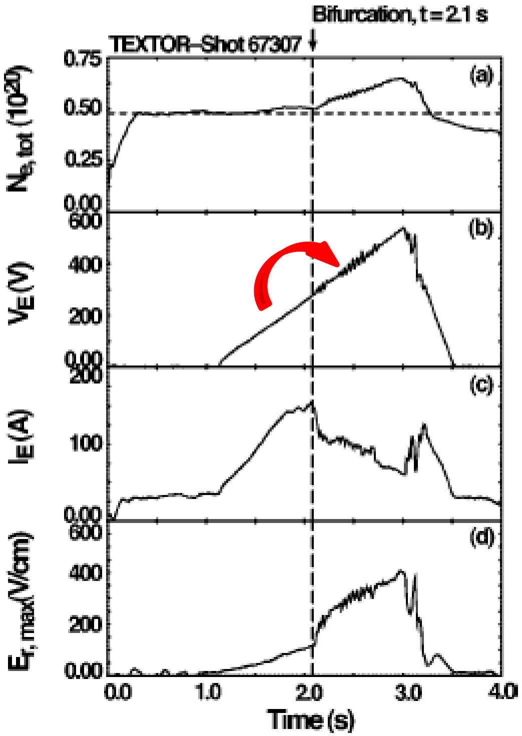


particle
content

biasing
voltage

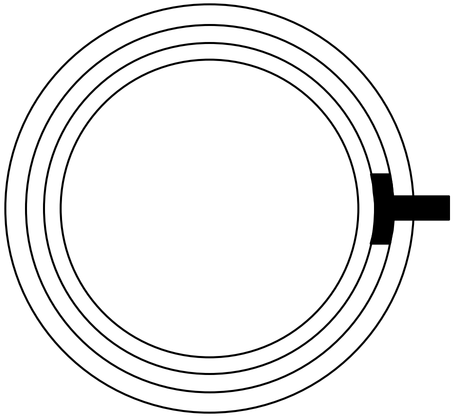
electrode
current

max E_r

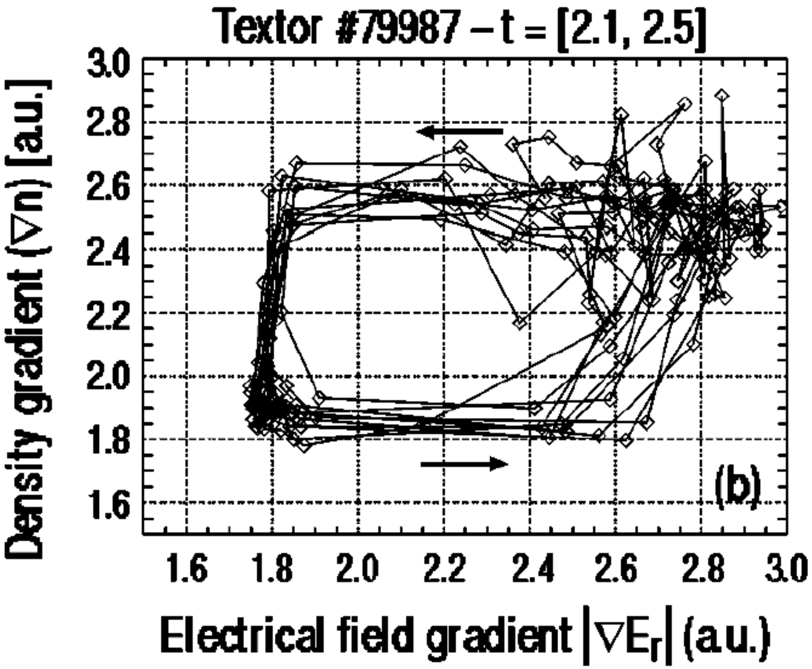


The causality chain: induced H-mode of TEXTOR

plasma
biasing



Lissajous orbit



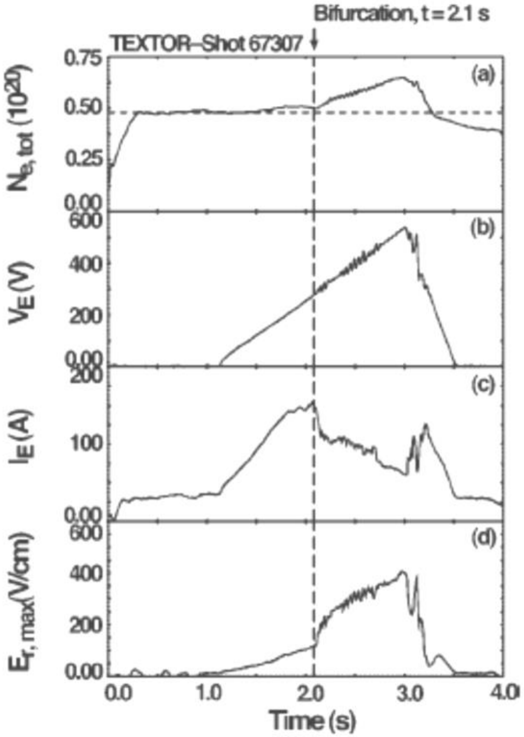
particle
content

biasing
voltage

electrode
current

max E_r

1990



voltage is sinussoidally modulated
E_r-field gradient change leads
density gradient follows after ~ 5 ms

R. Weynants, NF, 32,837,1992

Possible course of action from L- to H-mode

Increase of heating power toward power threshold

Edge gradients and fluctuation level increases in the L-phase

Asymmetry in poloidal fluctuation pattern allows the turbulent Reynolds stress to develop

e.g. via separatrix X-point, magnetic shear

The neo-classical mean-flow E_r-field is supported by the $\vartheta/\vartheta r(\langle v_r v_\theta \rangle)$-term

In the marginal state, the egde jumps between L- and H-mode (LCO)

The E_r field reduces the fluctuation level and the Reynolds term disappears again

The neoclassical E_r-field is large enough to stabilize the H-mode

Question: is a short-cut possible, without Reynolds Stress as mediator?

Obviously in case of ASDEX-Upgrade (M. Cavedon *et al* 2017 *Nucl. Fusion* **57** 014002)

General observations:

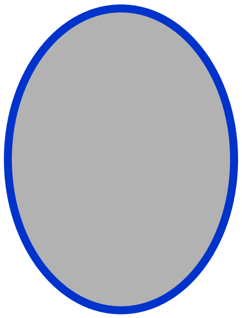
The response of a fusion plasma as a thermodynamically open system to increased power input can be a reduced level of turbulence.

Anomalous transport is a highly non-linear problem with self-regulating mechanisms, which can lead to the lowest dissipation state – collisional transport

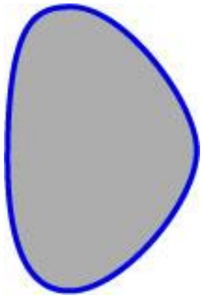
Improving the H-mode

Several strategies:

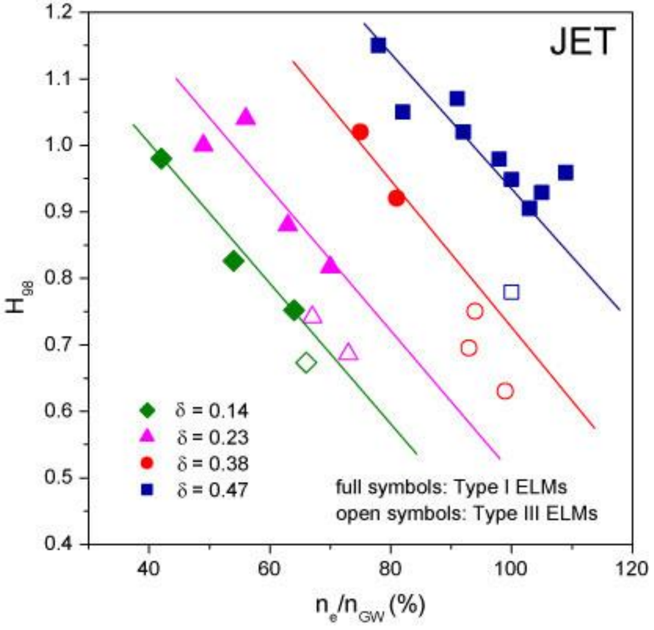
improved edge stability (increase edge pedestal)
avoiding, supressing ELMs
  via RMP (resonant magnetic perturbations)
  selected operational windows: ELMs are replaced by quasi-coherent edge instabilities
expanding edge pedestal
internal transport barriers (ITBs)



elongated



triangular δ



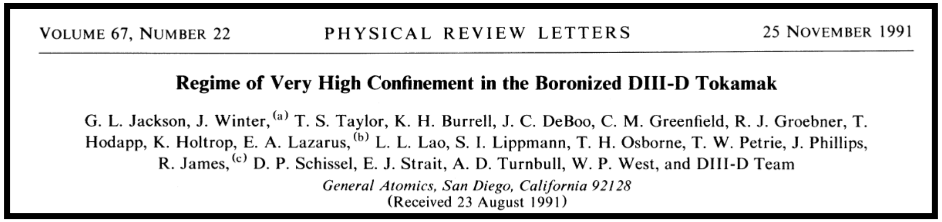
2003

From Saibene et al., 2003

Improving the H-mode

Expanding the barrier

VH-mode of DIII-D, 1991



VOLUME 67, NUMBER 22 PHYSICAL REVIEW LETTERS 25 NOVEMBER 1991

Regime of Very High Confinement in the Boronized DIII-D Tokamak

G. L. Jackson, J. Winter,(a) T. S. Taylor, K. H. Burrell, J. C. DeBoo, C. M. Greenfield, R. J. Groebner, T. Hodapp, K. Holtrop, E. A. Lazarus,(b) L. L. Lao, S. I. Lippmann, T. H. Osborne, T. W. Petrie, J. Phillips, R. James,(c) D. P. Schissel, E. J. Strait, A. D. Turnbull, W. P. West, and DIII-D Team

General Atomics, San Diego, California 92128

(Received 23 August 1991)

high density ($n_e(0) \sim 10^{20}$ m^{-3})
high T_i (13.6 keV)

H-factor: 3.5 !

ELMs replaced by quasi-coherent edge instability

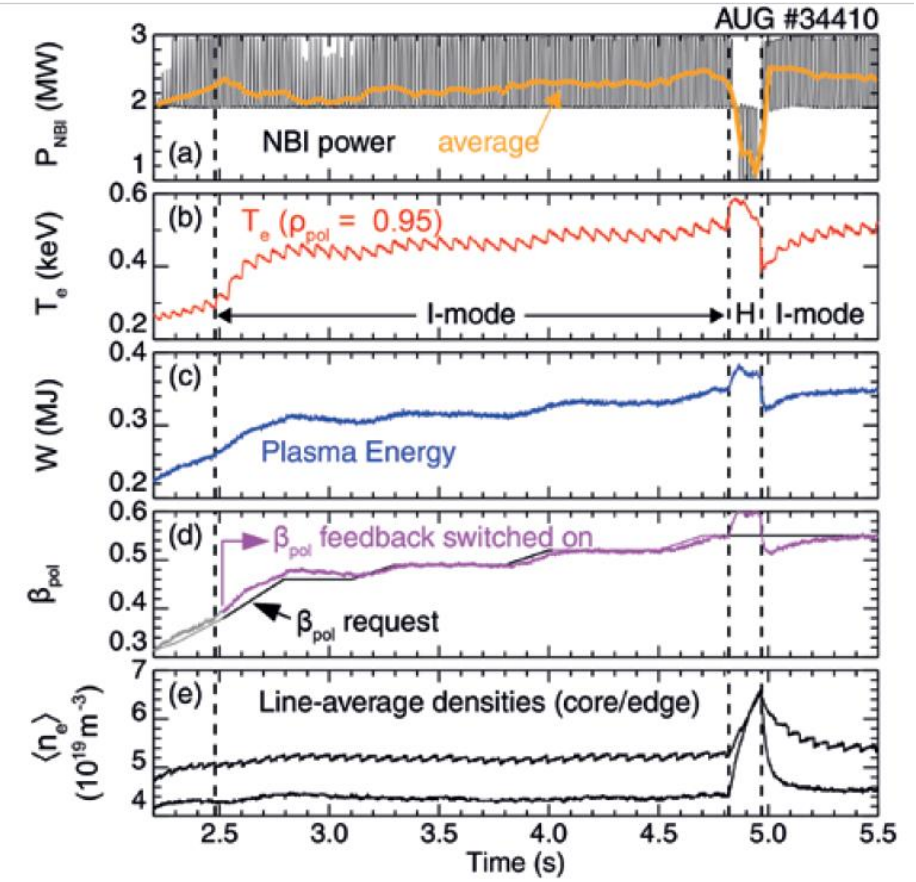
EDA-mode of Alcator C-mod
with QC-edge mode 2000

QH-mode of DIII-D
with EHO at the edge 2002

I-mode of Alcator C-mod
with WCM at the edge 2010

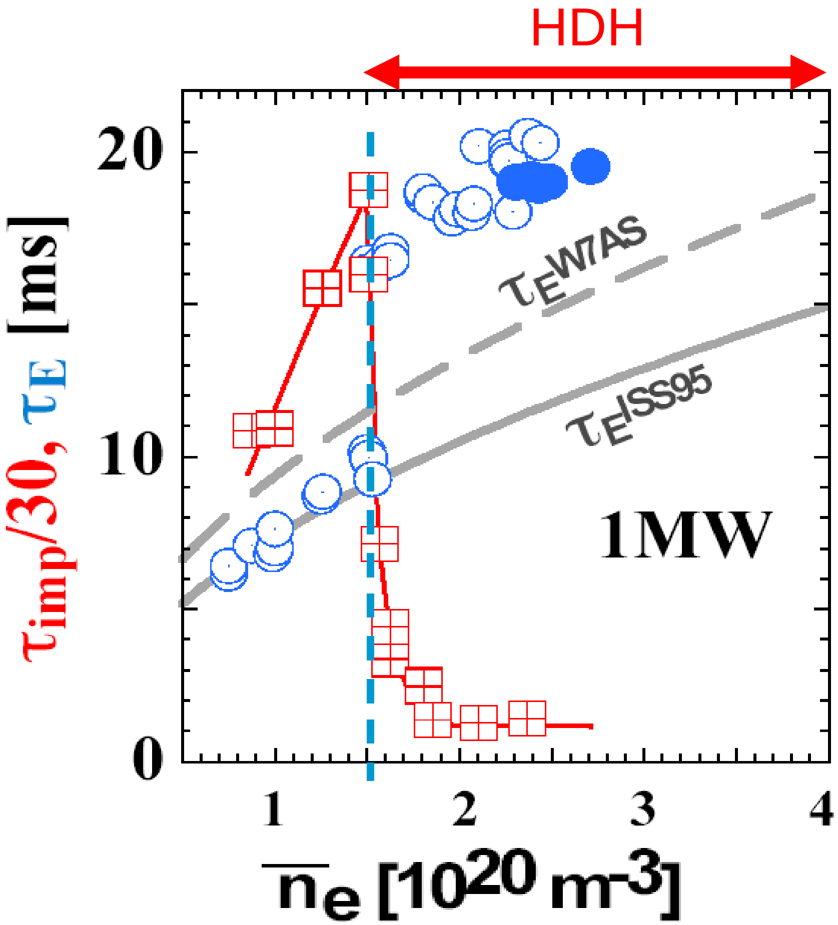
Improving the H-mode

Stationary I-mode of A-UP



T. Happel
ASDEX Upgrade Letter | 3, 2018

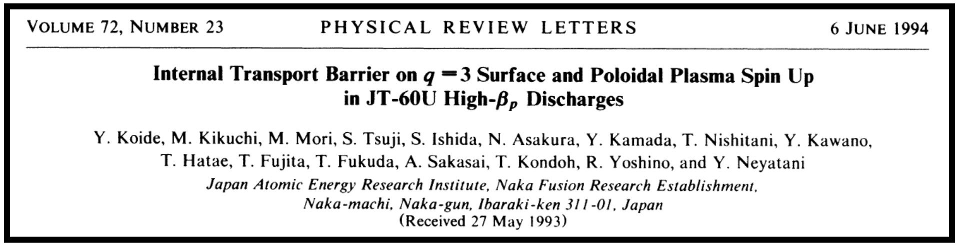
HDH regime of W7-AS, 2002



Improving the H-mode

Internal transport barriers

of JT-60 U, 1994



VOLUME 72, NUMBER 23 PHYSICAL REVIEW LETTERS 6 JUNE 1994

Internal Transport Barrier on $q = 3$ Surface and Poloidal Plasma Spin Up in JT-60U High-β_p Discharges

Y. Koide, M. Kikuchi, M. Mori, S. Tsuji, S. Ishida, N. Asakura, Y. Kamada, T. Nishitani, Y. Kawano, T. Hatae, T. Fujita, T. Fukuda, A. Sakasai, T. Kondoh, R. Yoshino, and Y. Neyatani

Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, Naka-machi, Naka-gun, Ibaraki-ken 311-01, Japan

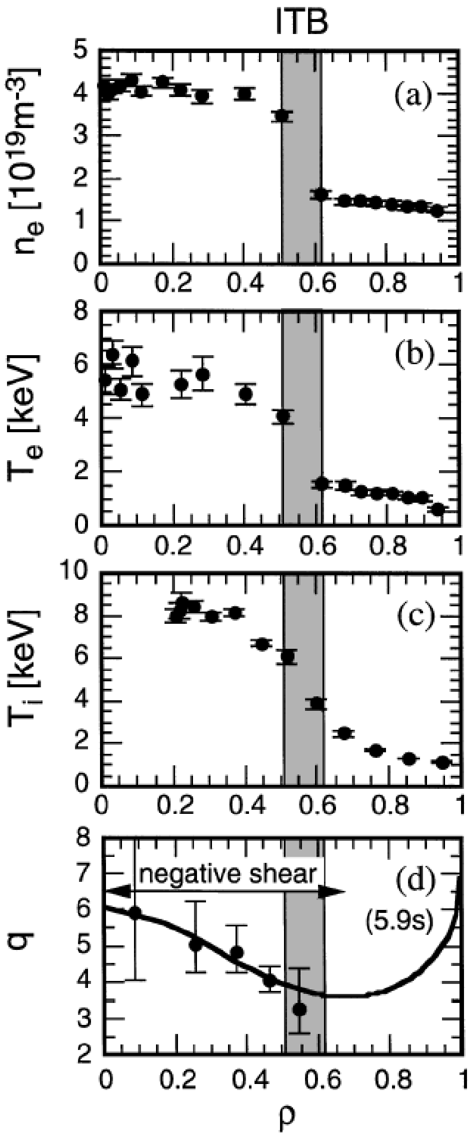
(Received 27 May 1993)

Tayloring of core-q-profile necessary
by flattening it or even reverse it

lowish I_p, high β_{pol}
off-axis heating
high bootstrap current fraction

Achievement in JT-60 U:

highest Q_{DD}



T. Fujita, PRL 78, 2377, 1997

Challenges

predict τ_E of ITER
good edge confinement without ELMs….

What I am interested in - 10 years after retirement:

Modelling of an H-transition without outside trigger

Understanding of the isotope effect

effect is know since 1973 (TFR)
first scaling: J. Hugill and J. Sheffield 1978 Nucl. Fusion 18 15
(devices for scaling studies: T3, T4, ST, Cleo, Ormak, Pulsator, TFR, Alcator, Tosca, PLT, T10)
is there an isotopic effect in stellarators?

Replacement of gas fuelling by pellets (or at least supersonic injection)

Physics of the current scaling.

tokamak scaling:

τ_E (L-mode, ITER 89) ~ $I_p^{\mathbf{0.85}} B^{0.2} R^{1.2} a^{0.3} \kappa^{0.5} A^{0.5} n_e^{0.1} P^{-0.5}$

τ_E (H-mode, ITER 98 y2) ~ $I_p^{\mathbf{0.9}} B^{0.2} R^{1.4} a^{0.6} \kappa^{0.8} A^{0.2} n_e^{0.4} P^{-0.7}$

stellarator scaling:

$\tau_E \sim \iota^{\mathbf{0.4}} B^{0.8} R^{0,7} a^{2} n_e^{0.5} P^{-0.6}$

with $\iota \sim I_p R/a^2 B \rightarrow I_p^{0.4} B^{0.4} R^{1.3} a^{1.2}$

Thank you very much

Thanks to those who organised the connection