Overview on LH-transition Experiments in helical Devices

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with contributions from
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the classical H-mode phenomenon

... close to H-mode observations in Tokamaks

The quiescent H-mode (H*) is marked by sudden suppression of turbulence
... order of magnitude in <100ms

H* is obtained at moderate heating power during density ramps.

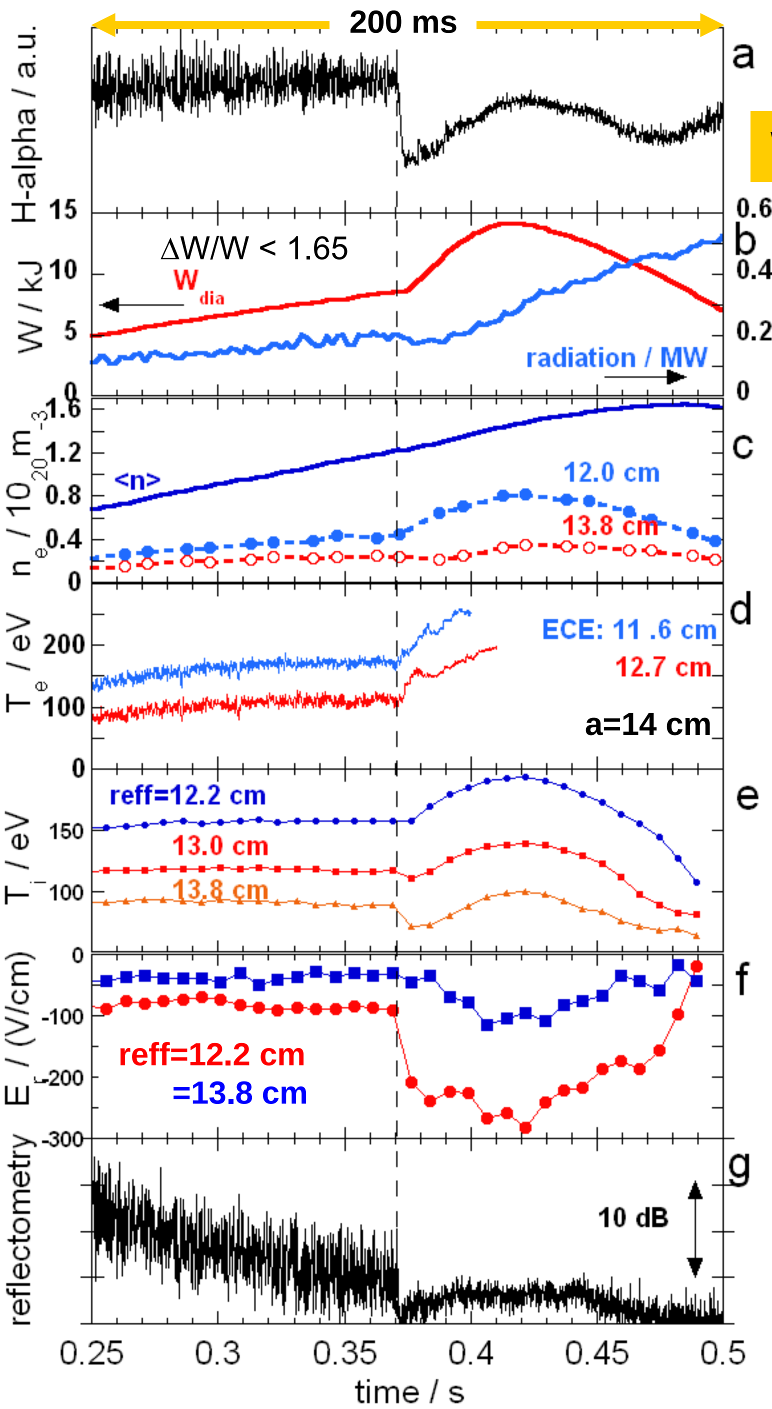
Edge gradients in **Ti**, **Te** and **ne** increase immediately

outermost 3-6 cm affected

a strongly sheared negative **Er** occurs

H* is transient (typically 50 - 100ms) due to impurity accumulation and radiation.

summary in
Hirsch et al, PPCF 50 2008



W7-AS

energy / radiation

grad(ne)

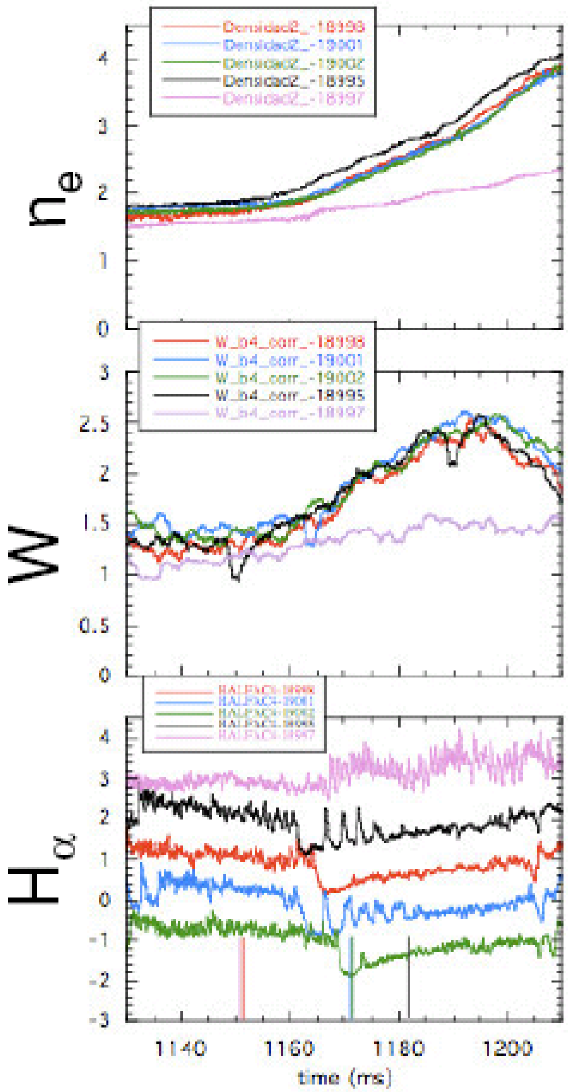
grad(Te)

grad(Ti)

grad(Er)

edge fluct.

H-mode in TJ-II



conditions: (next talk)

-> Li coated wall

-> certain P_{NBI} required, high density

-> configuration dependence

transition:

-> Te-unchanged within error bars

-> sudden reduction of turbulence

-> well of negative E_r evolves

-> ELMs

Sanchez_2009_NF
Estrada_2009_PPCF

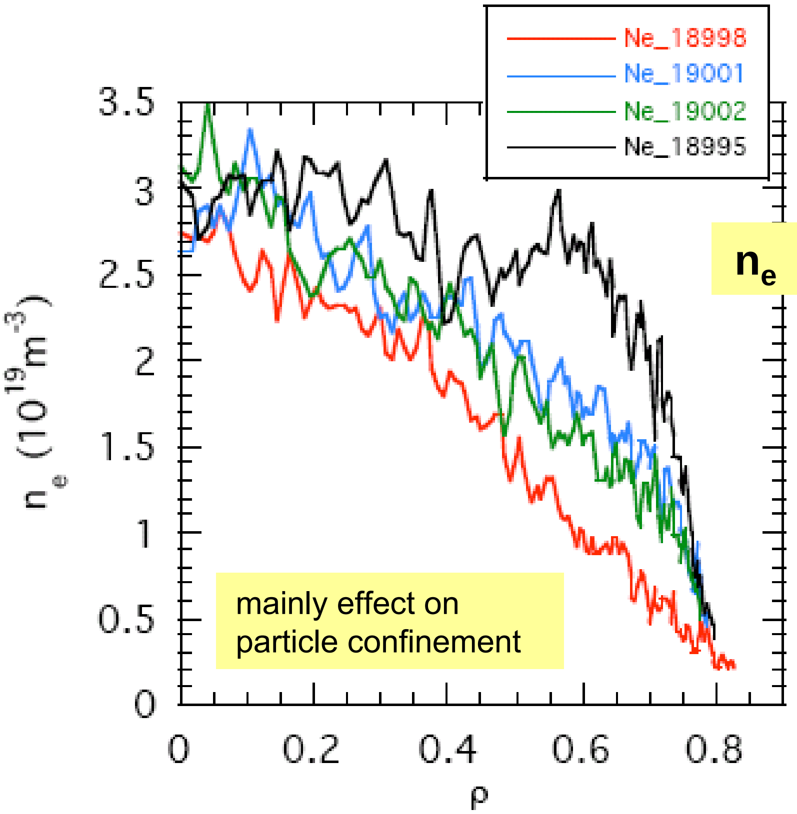


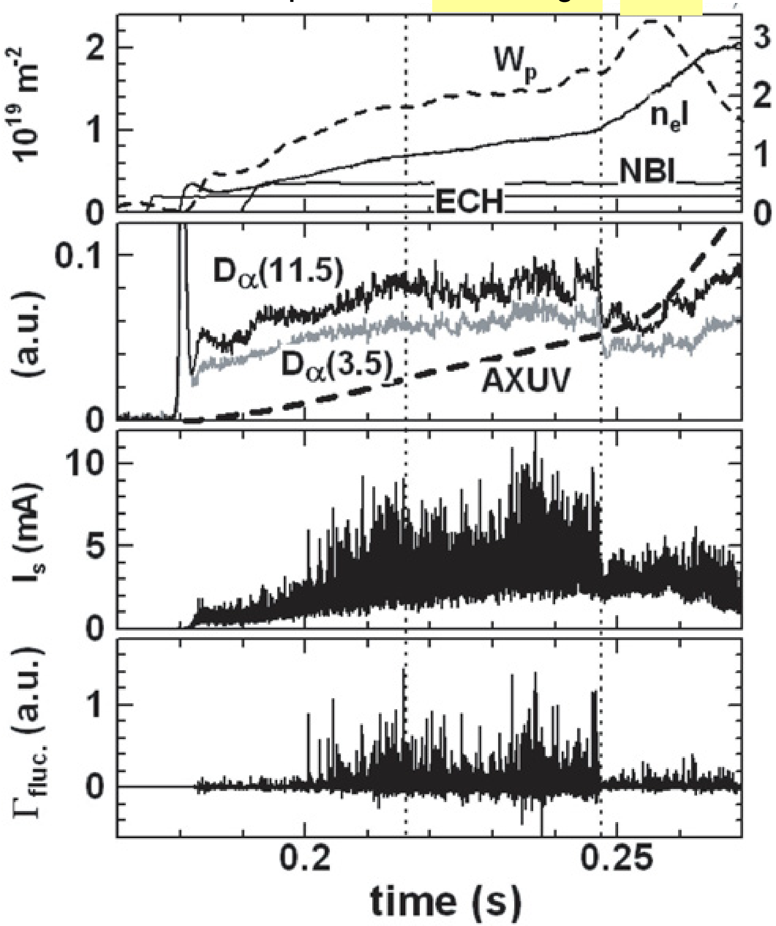
Figure 9. Evolution of the density profile during L-H transition

-> see following talk by T. Estrada

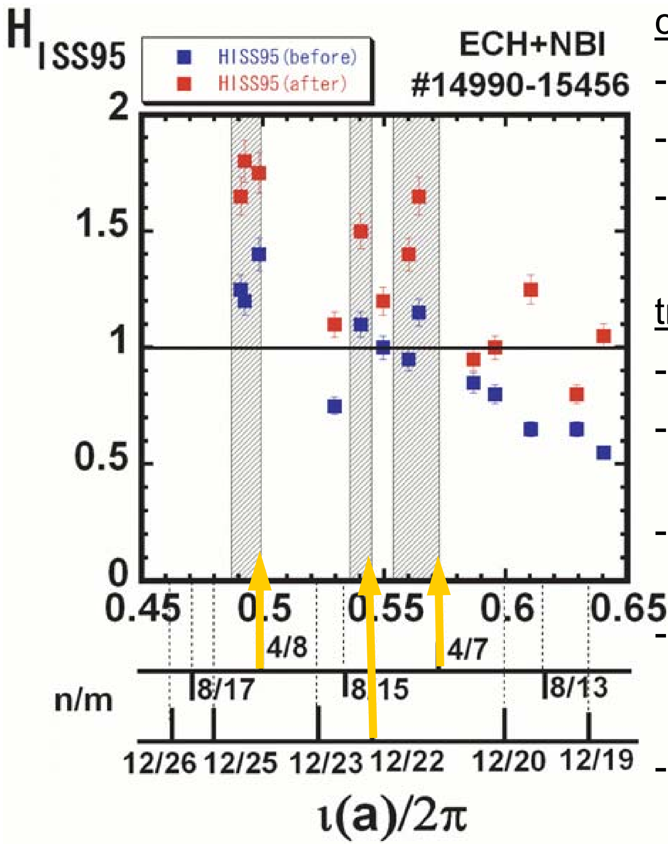
H-mode in Heliotron-J

He-J

transition in two phases: dithering → H*



iota-dependence of H-factor:



Sano_2005_NF

conditions:

-> config. dependence

-> min. power required

-> density threshold

transition:

-> two-step transition

-> profile data inside LCFS expected, not yet CXRS

-> probes indicate Er-shear layer (at innermost position)

-> rotation direction of filaments inverts at LH transition

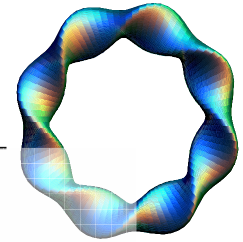
-> talk Nishino_Tue

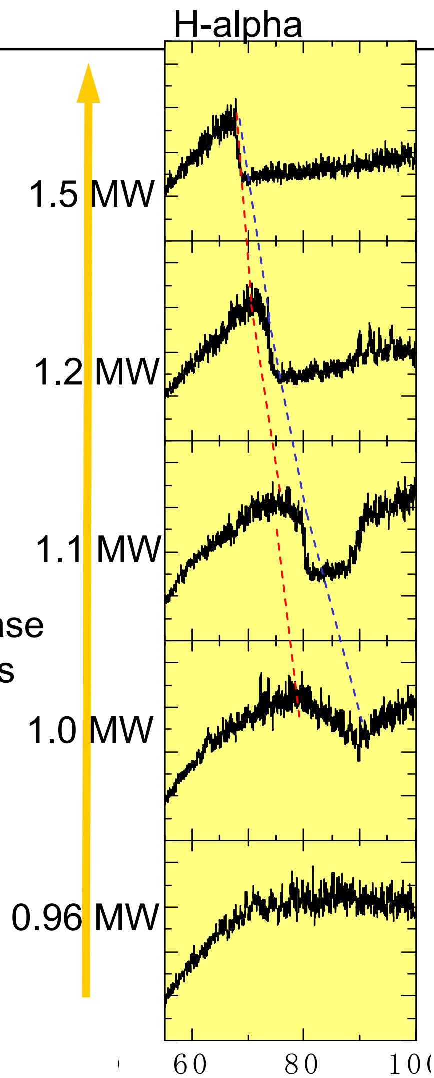
-> biasing experiments at low densities successful

-> talk by T Mizzuuchi today

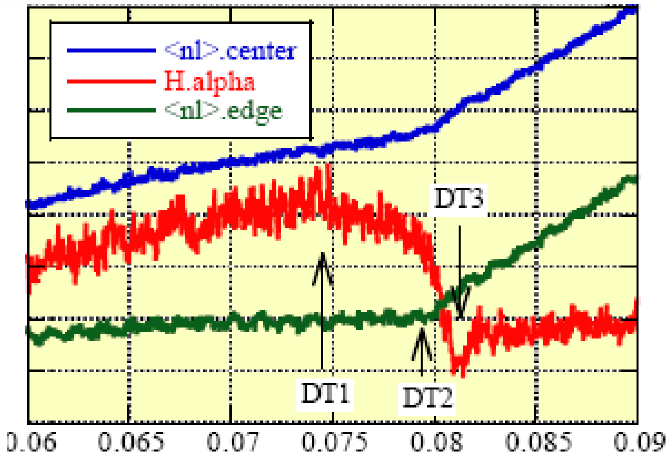
H-mode in CHS

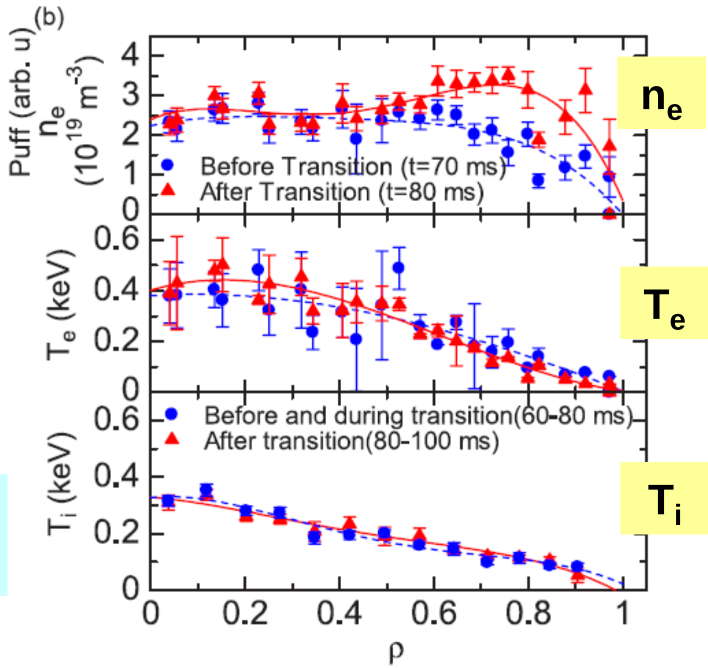
CHS





Akiyama_2006_PPCF,
Okamura_2004_PPCF





<u>conditions</u>:

-> inward shifted -> limiter edge

-> power threshold reduced if closer to separatrix-config

-> low n_e=2 10^{19} m^{-3}

-> mainly effect on edge density

<u>transition</u>:

-> two-step transition: several ms slow decrease of Hα and n-fluct before fast transition starts

-> back-transition after NBI terminated no hysteresis

-> no sudden turbulence suppresion

-> dithering if P=P_{thr}, no ELMs EHO with fully developed ETB

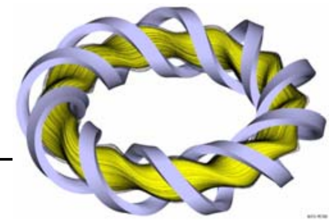
-> P_{thr} about factor 1 to 2.5 larger than ITER scaling

-> see poster by T Akiyama et al_Tue

H-mode-like transitions in LHD

... observations complex, summary still difficult - at least for me ...

LHD



conditions: Morita_2007_NF

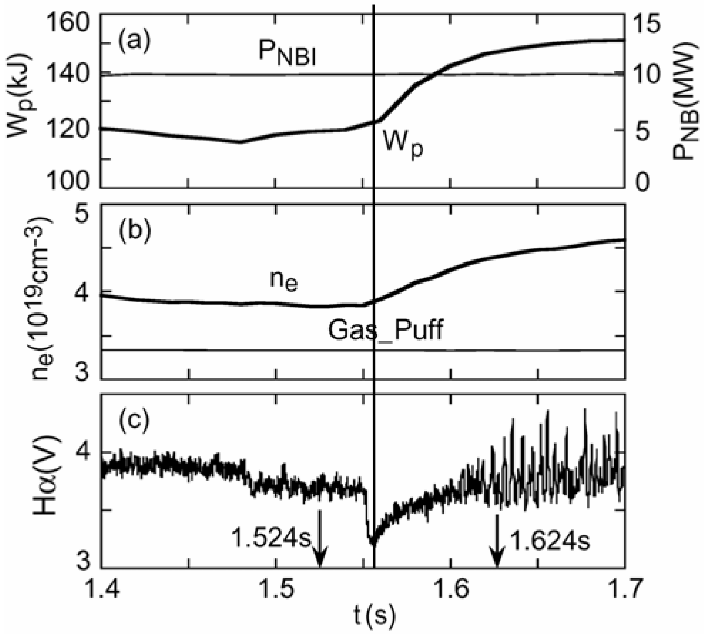
-> **transition with thick ergoidic layer in which iota=1 is embedded**
(R_{ax} outward shifted configuration)
-> power window, triggered by P reduction
Pabs > 1-2 times ITER H-mode threshold
-> density window 4-8 10^{19} m^{-3}
-> narrow R_{ax} configuration window

-> **2nd type of window or transition** in low-beta, low-Bt plasmas

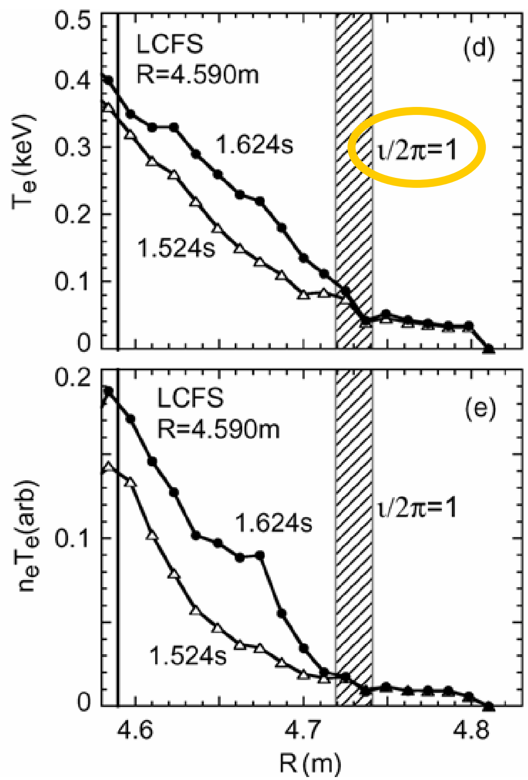
transition: Toi_2004_NF

-> reduction of mag. fluctuations
-> **ELM-like bursts**, even in low beta plasmas without LH transition
(Watanabe poster We)

spontaneos transition :



ergodic layer

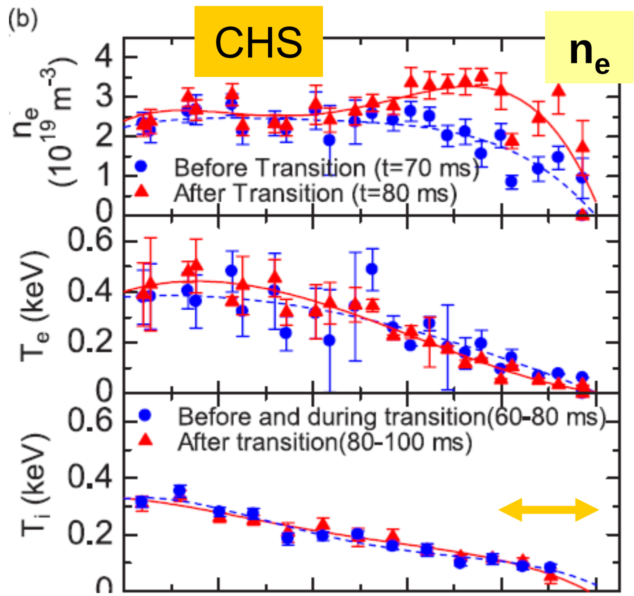


" ... related to P dependence of of plasma performance, particle screening by ergodic layer and position of iots=1/1 surface"

-> configuration with thick ergodic layer in which iota=1 is embedded

profiles: edge pedestal develops in H-mode

4 cm "pedestal width"



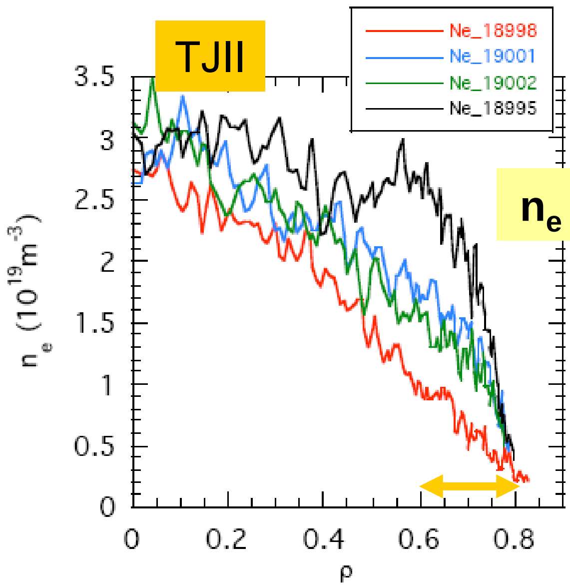
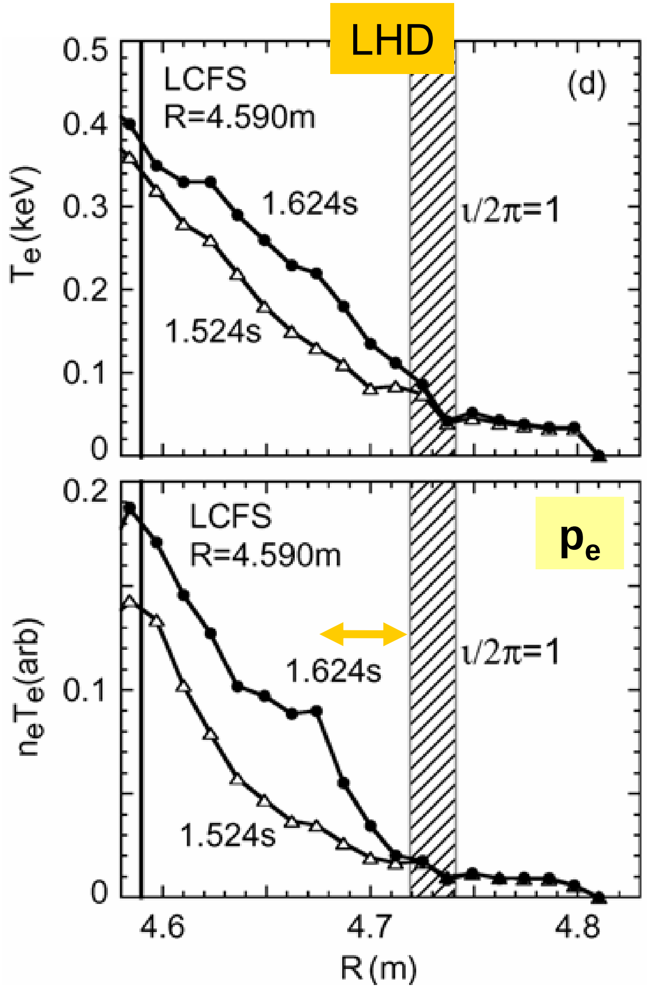
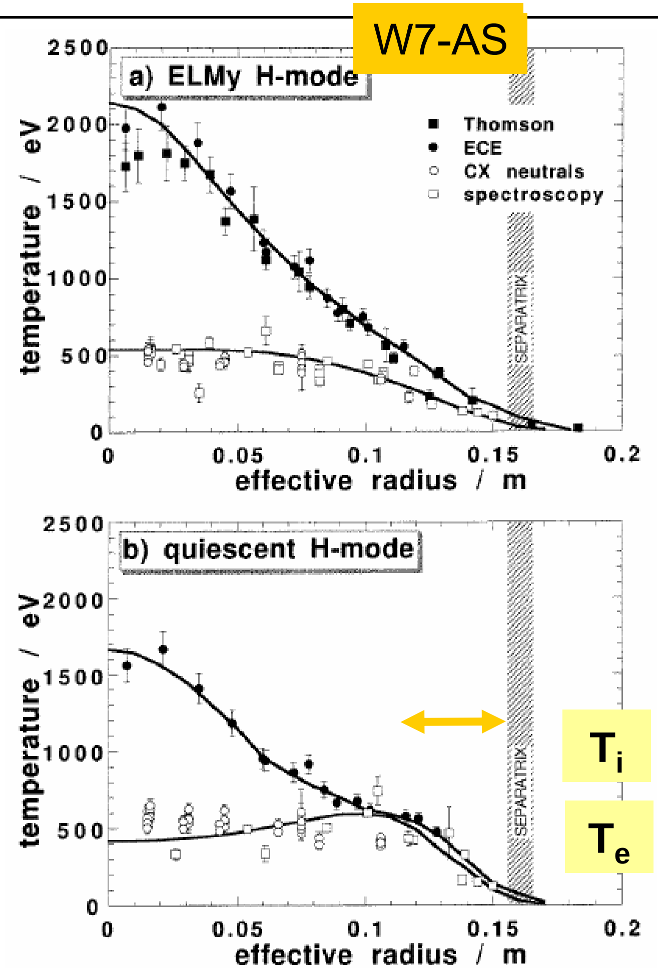


Figure 9. Evolution of the density profile during L-H transition





-> outermost 3-6 cm affected
(not dependent on machine size)

-> mainly effect on density profile ?
besides W7-AS

no "pedestal" in **ne profile** already
steep grad(n) before transition
-> grad(n) increases by factor <2
-> separatrix density often falls

He-J -> not yet known

dynamics: Edge Localized Modes

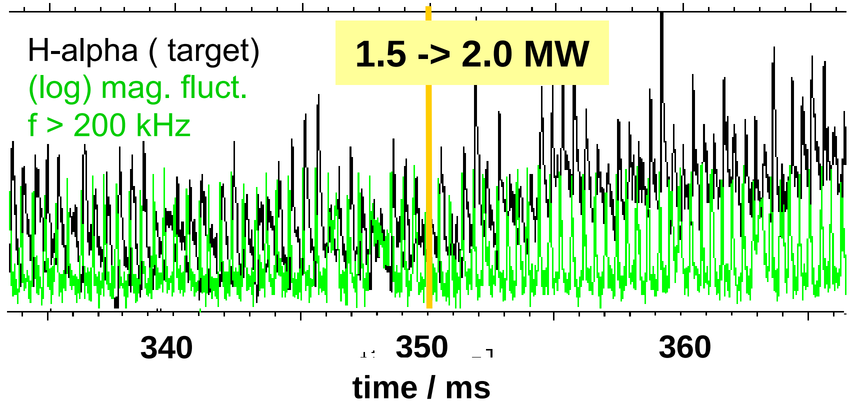
ELMs are distinct transport events with duration of 200 μs and show the **basic features also observed in tokamaks**

TJII -> **ELMs under investigation**

LHD -> **ELMs** phenomenology dependent on m/n=1/1 perturbation fields

ELMs occur in a wide configuration range by far exceeding the narrow windows for H* which is often reached through ELMy time intervalls.

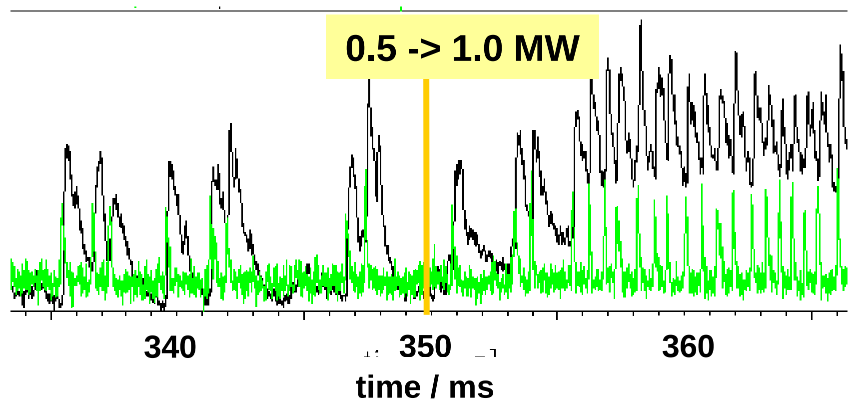
The **ELM phenomenology** depends on the magnetic configuration, the proximity to conditions for a final transition to H* and on ∇p.



W7-AS more :

Quasi periodic ELMy H-modes occur close to the conditions of a quiescent H-mode (?); they can be maintained stationary by density feedback.

Bunches of irregular ELM events interrupted by short quiescent phases with turbulence identical to H* are observed for large ∇p.



He-J -> **no ELMs**, dithering phase

CHS -> **no ELMs**

the **classical (quiescent and ELMy) H-mode** is close the references from Tokamaks

pecularities in helical devices exist with respect to operational range:

-> configuration dependence

-> role of (neoclassical) equilibrium Er (ion-root) as a (possible) bias with impact on P-threshold (?)

other ETB regimes, "H-modes" are possible, eg. relying on the mean shear flow

-> Similar effects of turbulent transport reduction (e.g. dominated by the mean shear flow instead of dynamic sheared flows and thus but probably without fast bifurcation

working hypothesis:

Consider the **classical H-mode in W7-AS** as fast **bifurcation** of turbulence, flows and ExB velocity **on top of** the **equilibrium conditions of the stellarator edge** (defined by Er and momentum balance) which allow for confinement bifurcation.

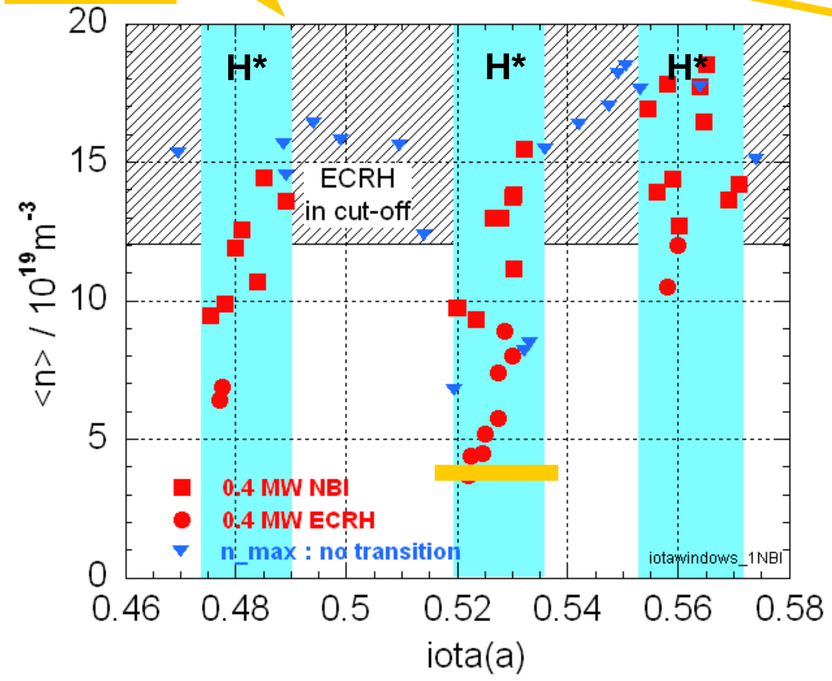
... a "configuration biased" H-mode ?

1) the importance of configuration / edge topology

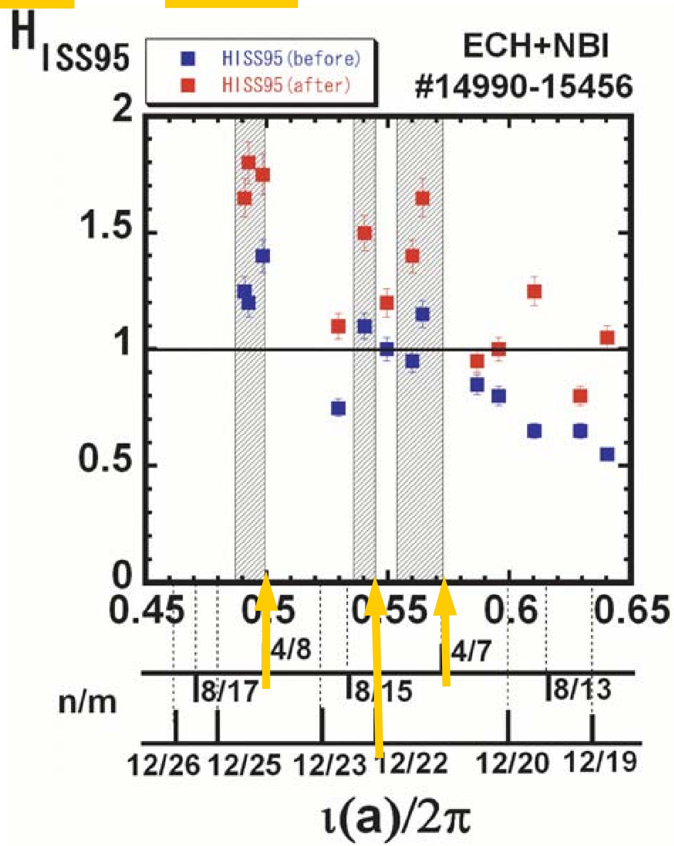
1) low-shear:
iota-dependence of **H***:

2) classical large-shear Heliotrons
CHS: limiter H-mode only (Rax inward shiftd)
LHD: Rax-window (thick ergodic layer embracing iotaa=1?)

W7-AS



He-J TJ-II **-> see next talk by Estrada**



highly reproducible windows of the edge rotational transform.
... within this sharply defined windows and density it is
practically unavoidable

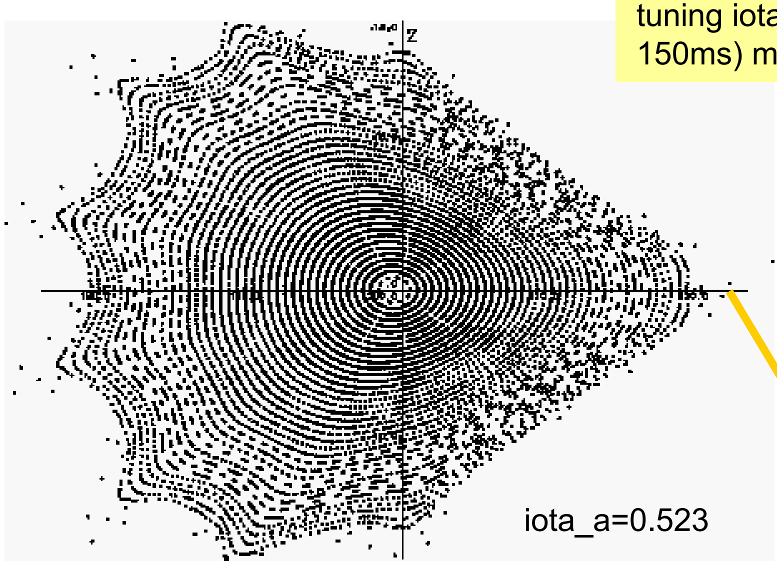
H-factor large if iota is slightly less than the values of the major natural resonances

ELM phenomenology depends strictly on configuration
- also a link to current tokamak research

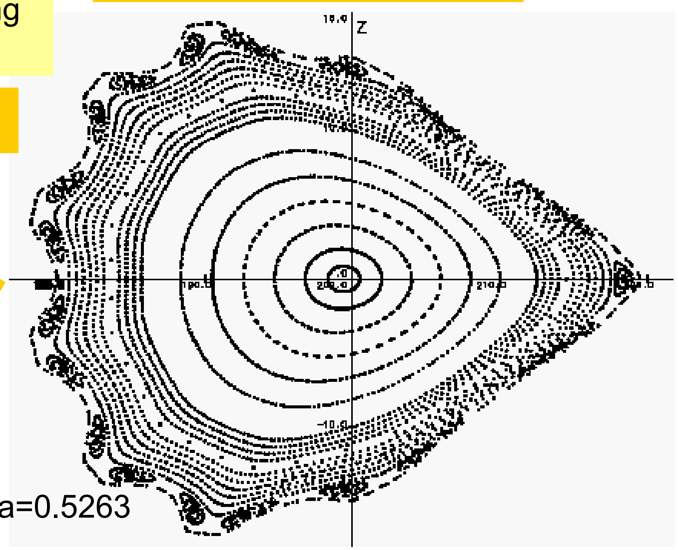
W7-AS, LHD, (TJ-II ?)

tuning iota across a H-mode window (during 150ms) modifies ELM-phenomenology !

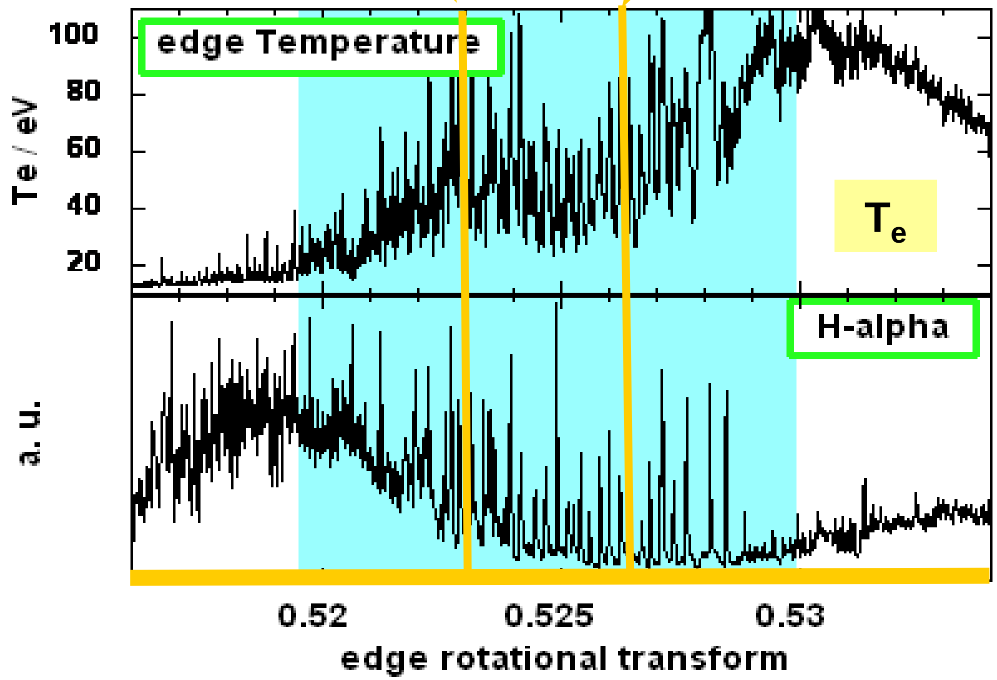
W7-AS



iota_0=0.5017



iota_0=0.5097



-> a stellarator specific knob for ELM mitgation

(common with current tokamak research: "ELM mitigation by 3D magnetic perturbation")

sensitivity to configuration: understanding ? - no, but hypotheses exist

1) the iota windows are characterized by :

minimum of poloidal viscosity right *inside* LCFS
(= minimum magnetic pumping)

W7-AS: : **but not all windows**
He-J : yes

Wagner_1994_PPC
Wobig_1997_EPS
Sano_2005_NF

2) the iota windows are characterized by :

a well defined grad(Er) already *prior to* LH

-> *outside* LCFS: small x-point target distance -> steep decrease of connection length (positive Er!) *inside* LCFS: ion-root (negative Er !) (**but contradiction:** He-J !)

3) rationals may trigger (sheared) flows

Hidalgo_2000_PPCF, Ida_2002_PRL, Estrada_2009_PPCF, talk Finken, We

LHD **-> m/n=1/1 ialand at edge**

TJ-II **-> next talk**

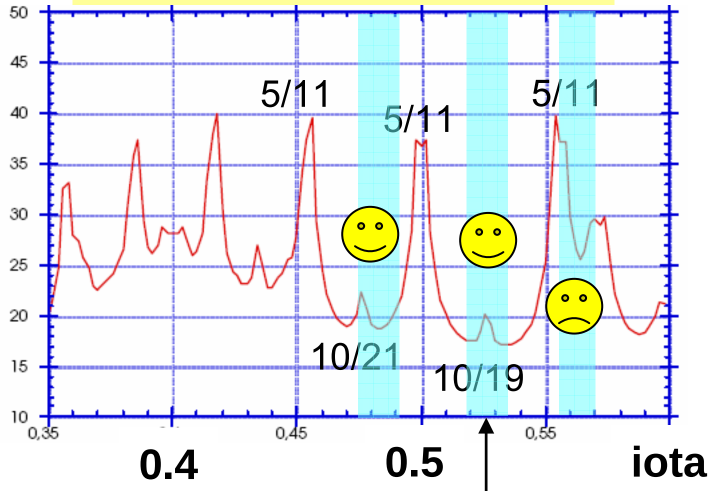
4) B_{mod} structure on flux surfaces (optimization) couples to flows

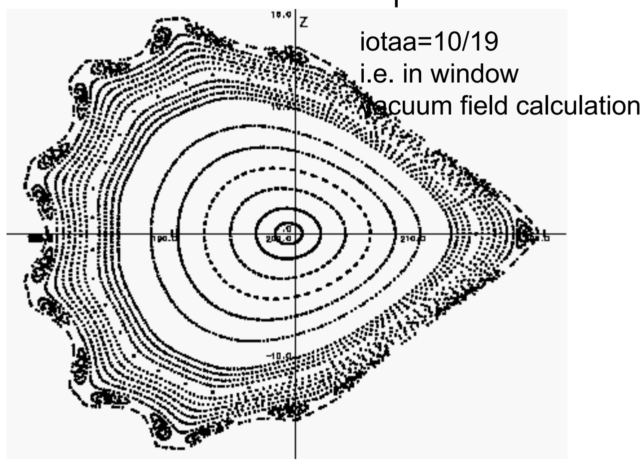
e.g. influence of geodesic curvature on zonal flows !

W7-AS, He-J, .. **-> see e.g. talks by Helander, Sugama, Mo**

W7-AS

neoclassical poloidal viscosity





edge determined by 5/9 islands
and smoothed by smaller ones

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W7-AS

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decrease of connection length (pc
root (negative Er !) (**but contradi**

-> study edge geometry + viscosity and drive with improved equilibrium codes (e.g. HINT2) including finite-β and j_{BS} effects

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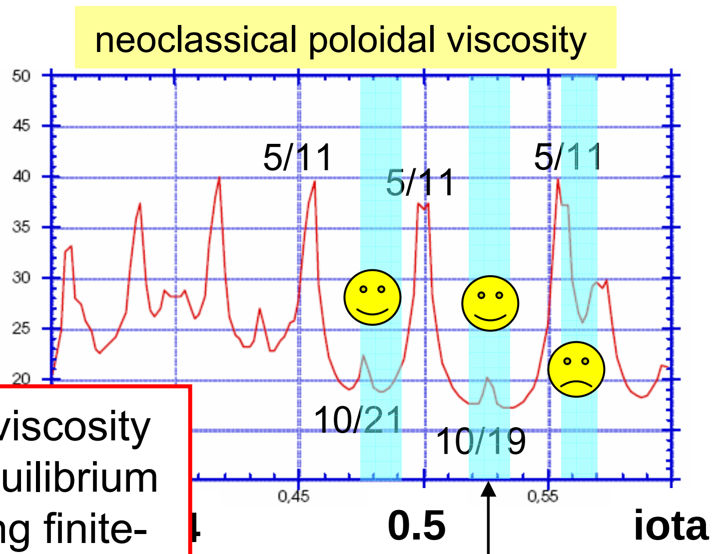
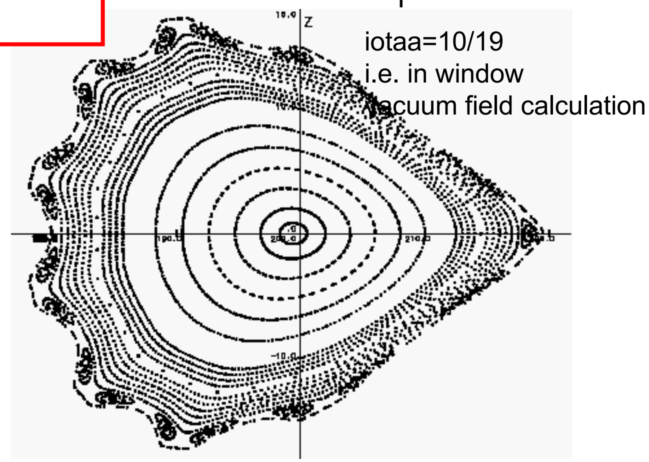


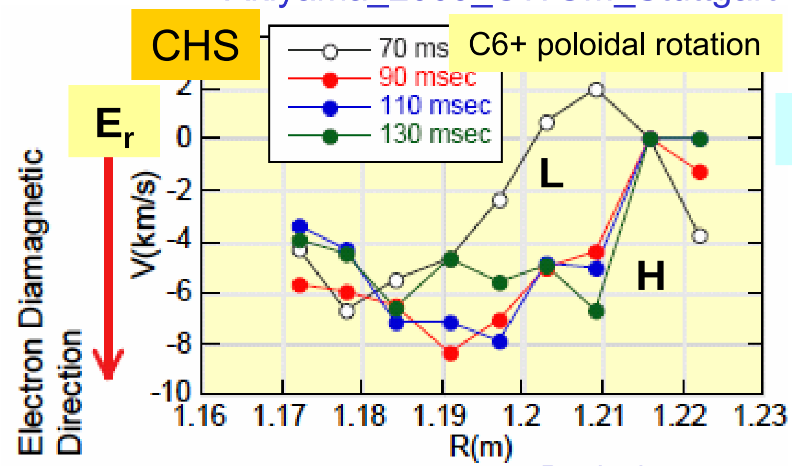


edge determined by 5/9 islands and smoothed by smaller ones

2) ExB flow shear and turbulence

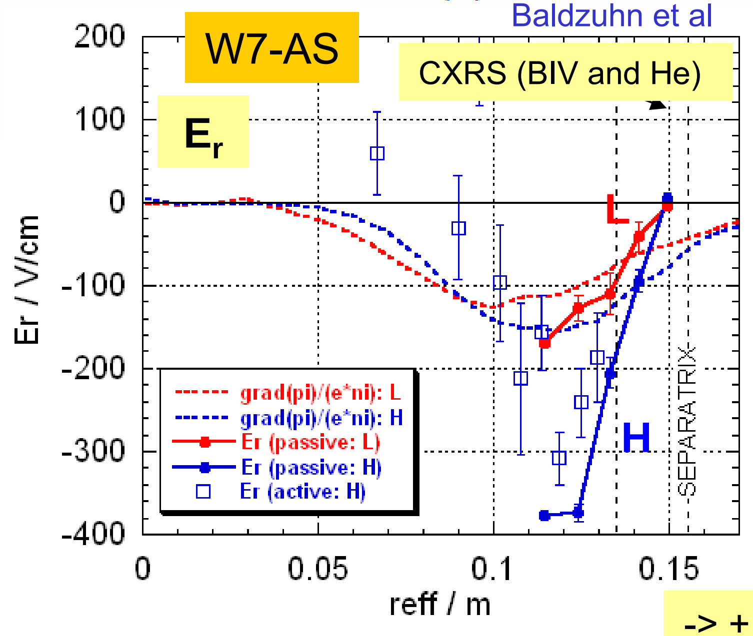
paradigm for the classical H-mode:
suppression of turbulence by (dynamic) sheared flows

Akiyama_2009_CWGM_Stuttgart



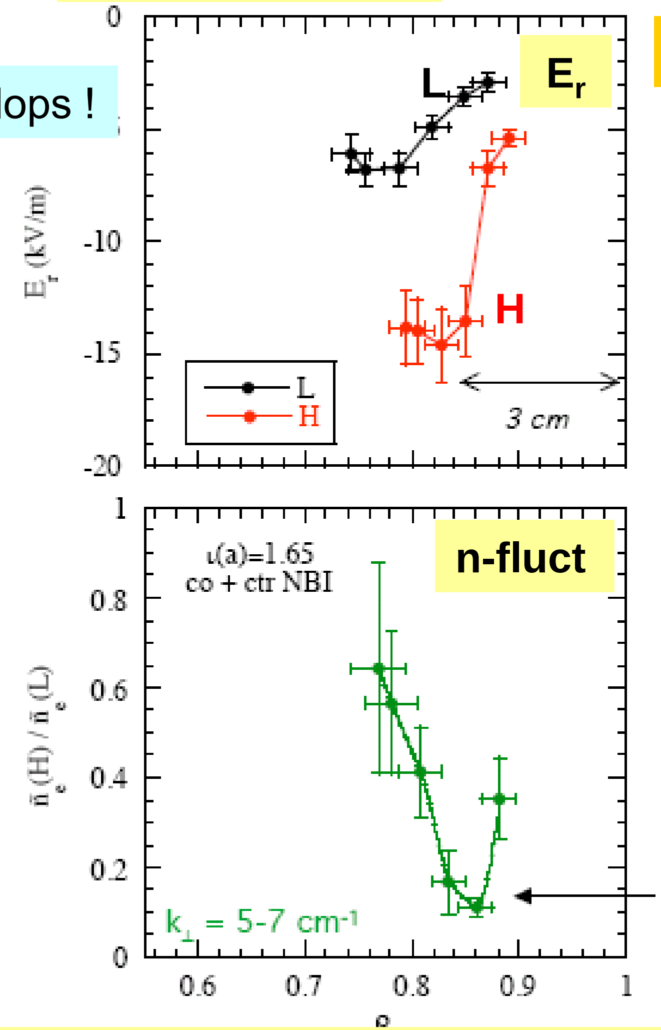
negative Er develops !

Baldzuhn et al



Doppler Reflectometry

Estrada_2009_PPCF

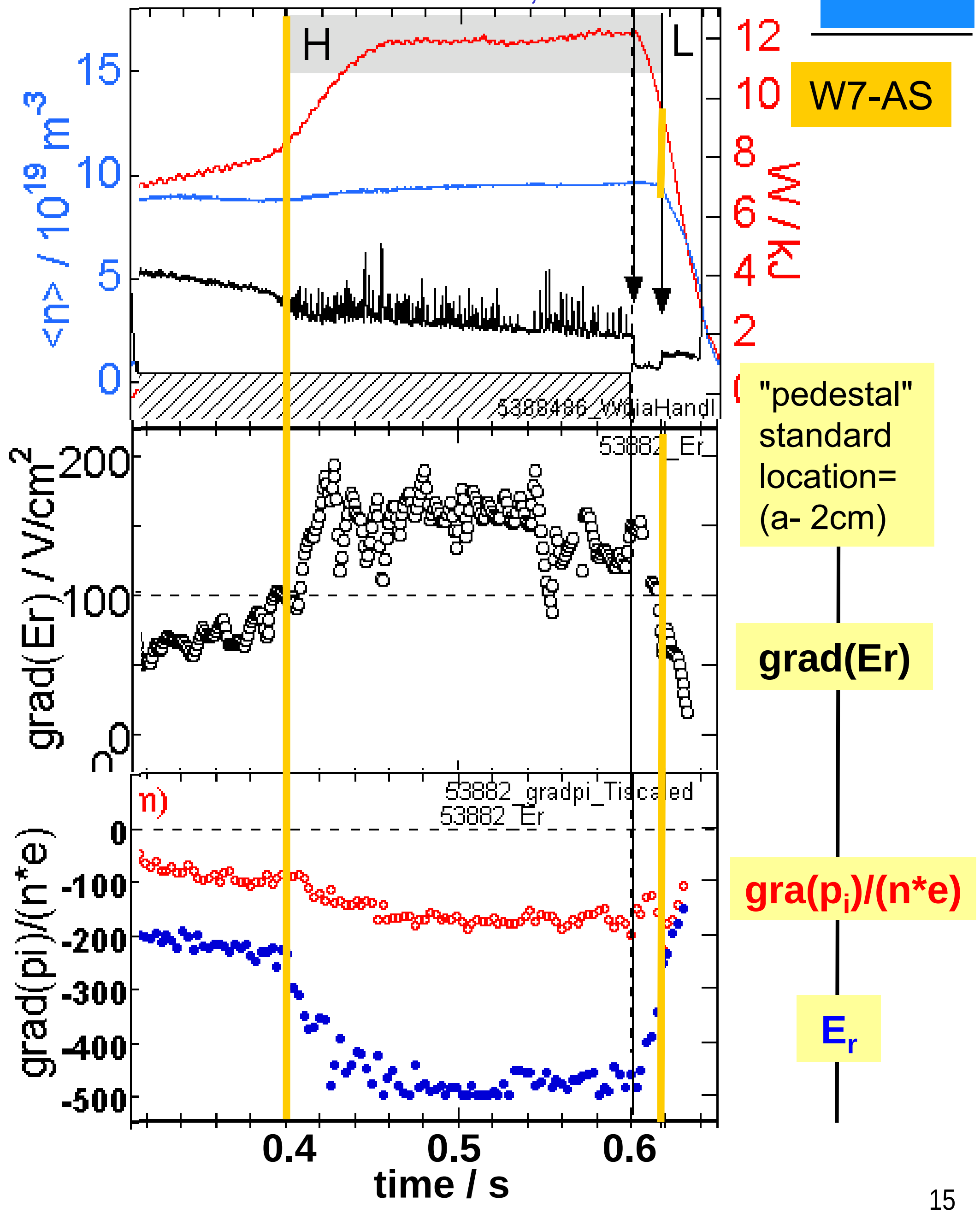


-> + biasing experiments (Tohoku, He-J, TJ-II) confirm active impact by Er

radial electric field Er and bifurcation character

-> spontaneous transition and back-transition

Badzuhn, Hirsch et al



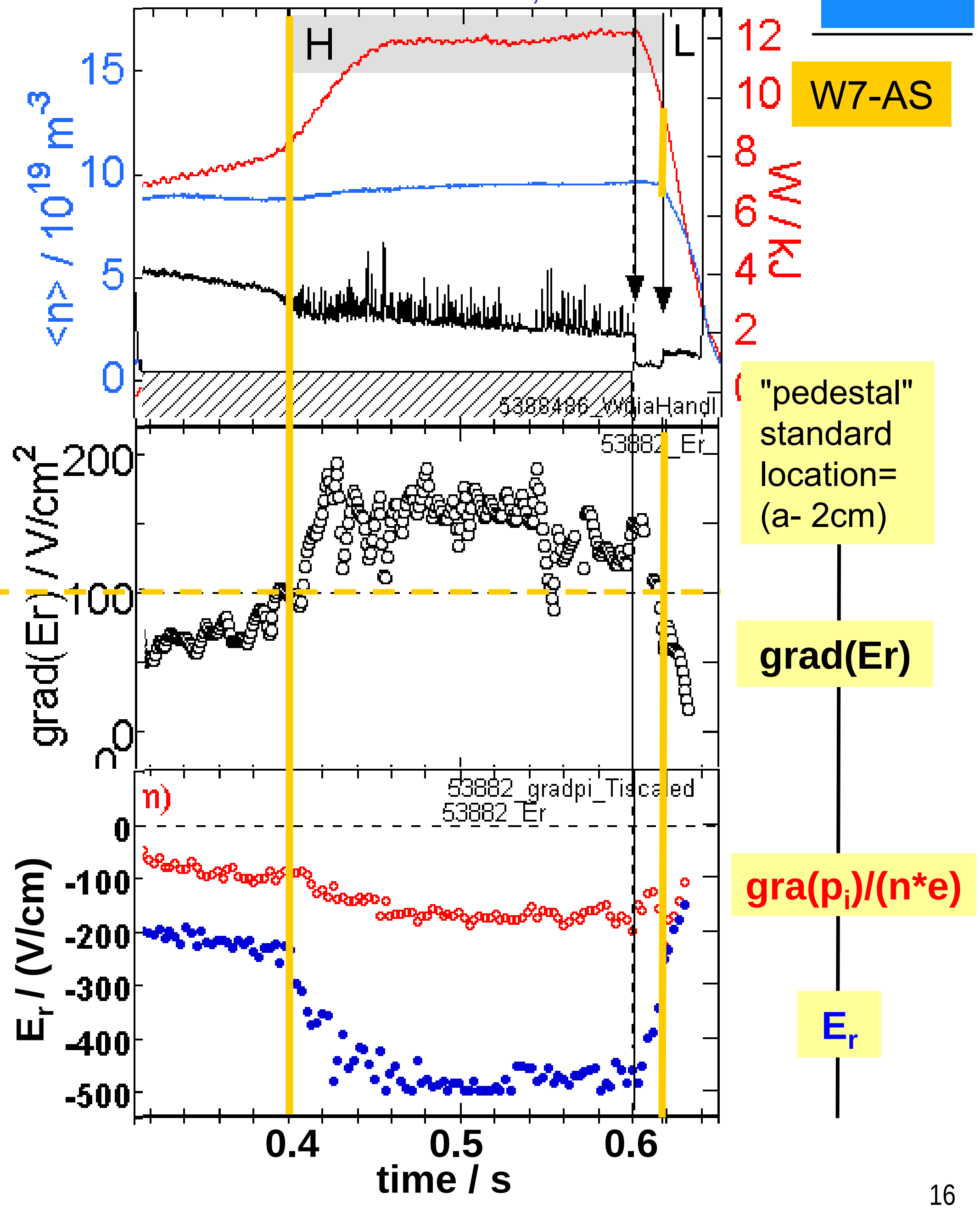
radial electric field Er and bifurcation character

-> spontaneous transition and back-transition

-> **LH and HL** occur at a certain value of grad(Er)= typ. 50-100 V/cm indicating a threshold.
No hysteresis observed.

... the decisive *local* quantity ?

Badzuhn, Hirsch et al



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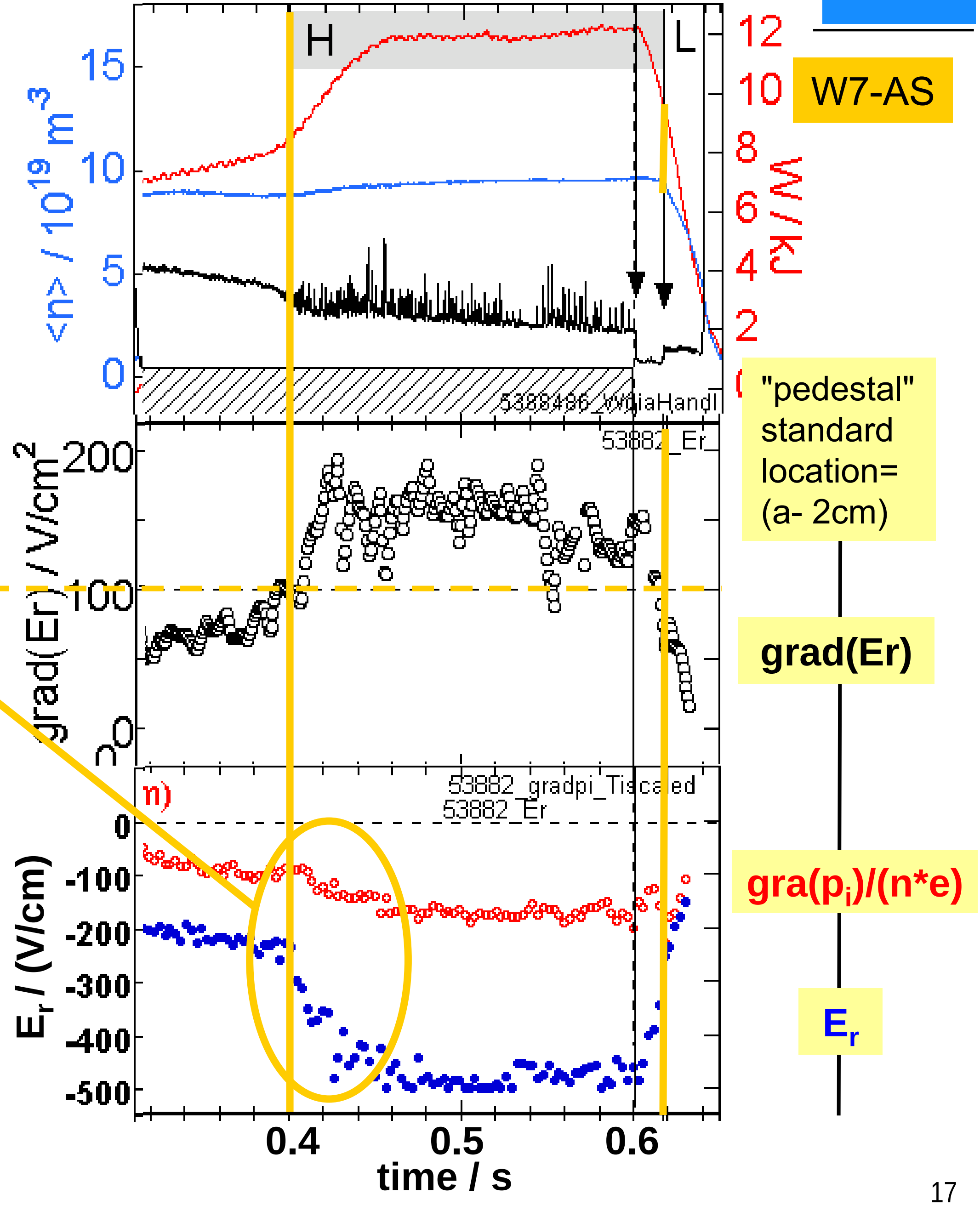
-> **before H-mode**:
Er is close to neoclassical ion-root predictions (-> already moderate to large negative Er).

-> **after the L–H transition**:
The well in Er(r) existing already from the ion-root conditions deepens at the same radii where pressure gradients steepen **but by a factor of up to 2 more than expected from the increase in** ∇ **pi/(e · n) alone**.

Badzuhn, Hirsch et al



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The well in Er(r) existing already from the ion-root conditions deepens at the same radii where pressure gradients steepen **but by a factor of up to 2 more than expected from the increase in ∇pi/(e · n) alone**.

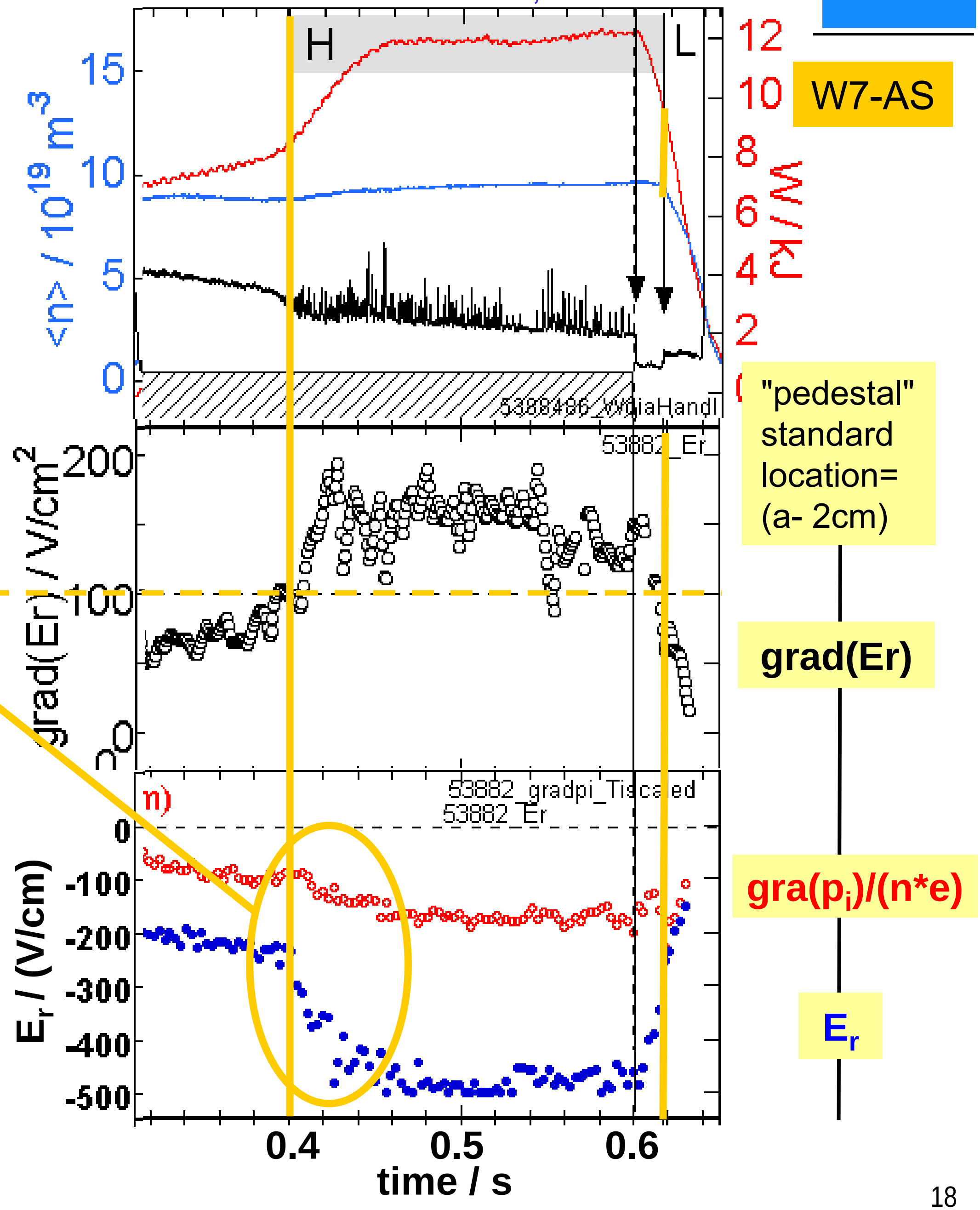
-> Thus in the radial force balance of the bulk ions,

$$Er = \nabla pi/(e \cdot n) - B\theta \cdot v\varphi + B\varphi \cdot v\vartheta$$

besides the <u>diamagnetic term</u> *Er* is balanced by a strong contribution from ***poloidal*** *vxB* rotation of the bulk ions.
(also found in TJ-II) <-> to Tokamaks ?

Estrada_2009_PPCF

Badzuhn, Hirsch et al



bifurcation character: E_r at the H-L back-transition

W7-AS

HL-back transition:

E_r decreases by about 80 V/cm within < 2ms

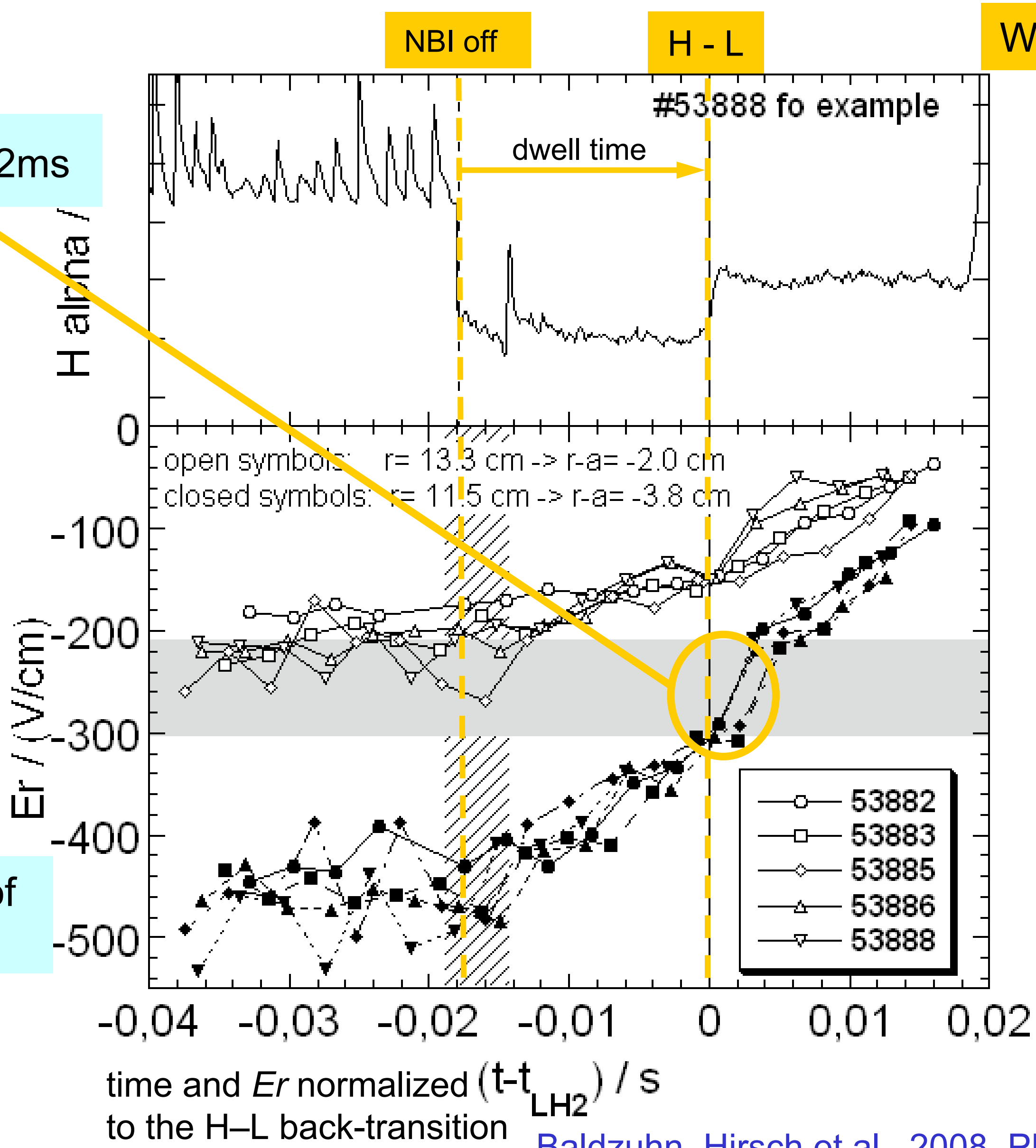
<u>the causality question</u>:

-> the H-mode contribution to pol ExB rotation ?

OR

-> sudden break of pol. rotation due to increasing turbulence ?

-> classical H-mode contribution on top of the equilibrium (neoclassical) E_r ?



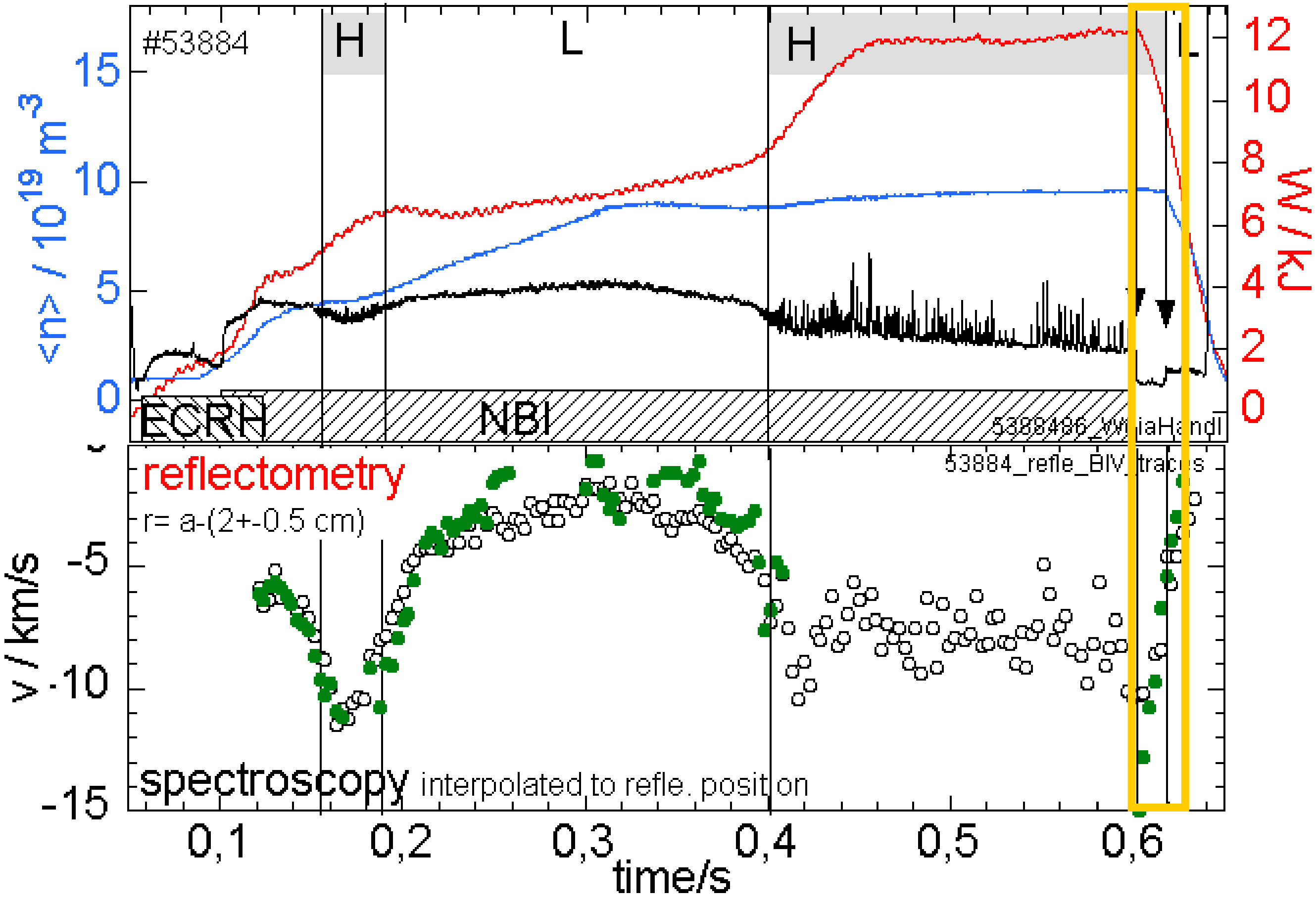
Baldzuhn, Hirsch et al_ 2008_PPCF

turbulence rotates with ExB velocity during L- *and* H-mode

at least on spectroscopy timescale (order 1 ms)

W7-AS

Doppler reflectometry:
backscattered intensity
-> turbulence amplitude
Doppler shift
-> turbulence propagaton



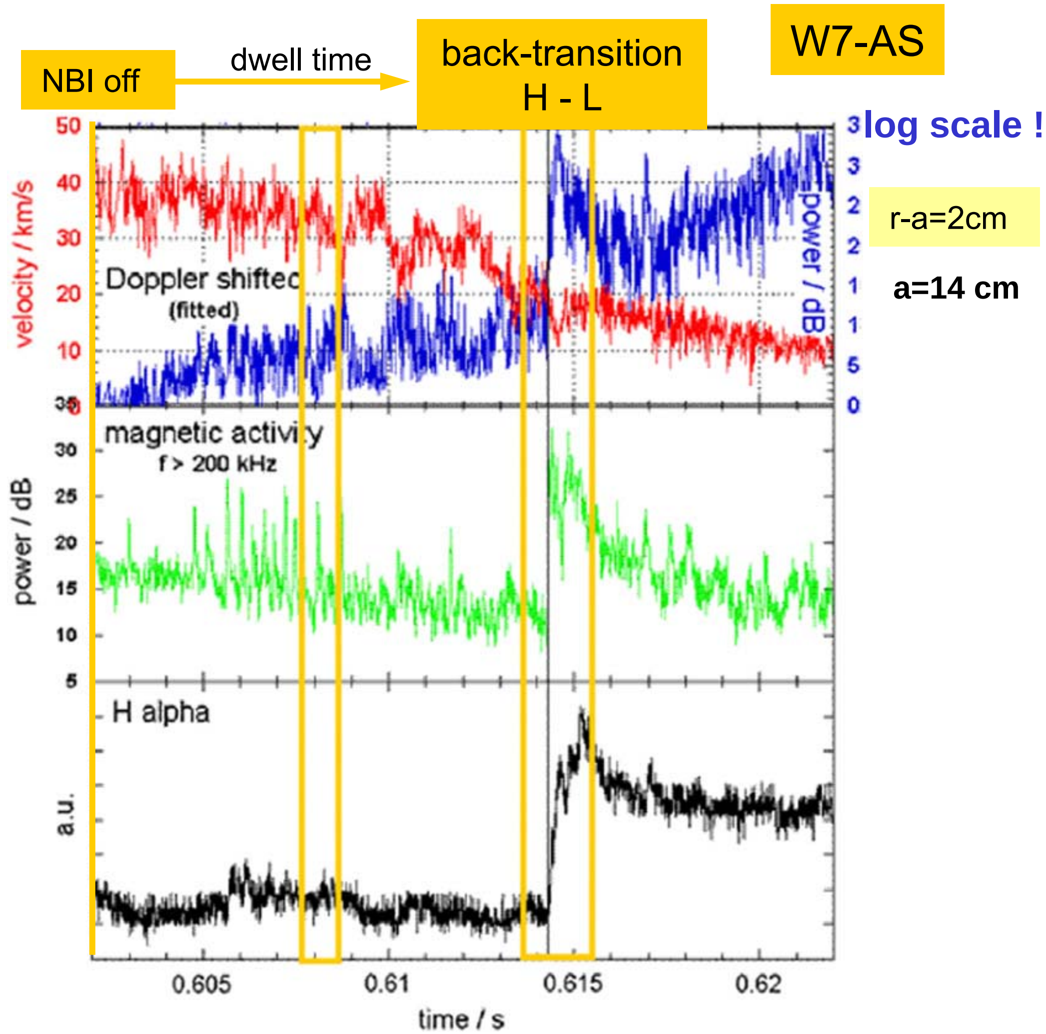
v_{turb} from Doppler Reflectometry
and
v_{ExB} from **impurity spectroscopy**

-> confirmed **in (W7-AS, AUG, Tore Supra, TJ-II)**
from comparing **radial profiles** of v_{turb} (Doppler Reflectometry)
with v_{ExB} profiles from spectroscopy or HIBP

Hirsch_2001_PPCF
Schirmer_2006_NF
Hennequin_2005_IRW7
Estrada_2009_PPCF

the classical H-mode: a bifurcation of turbulence and flows ?

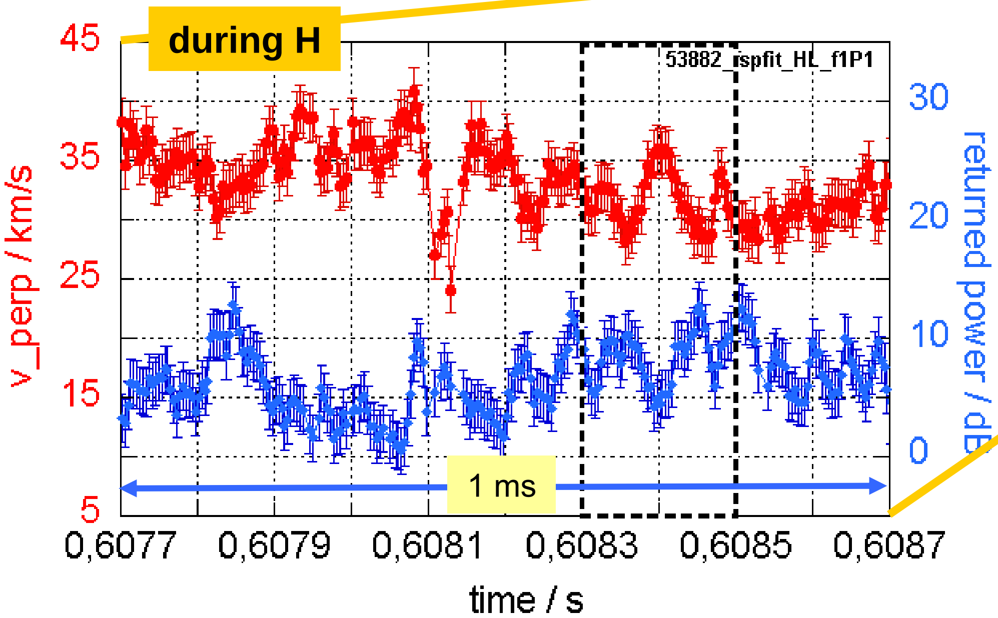
ploidal propagation velocity of turbulence
and the qualitative turbulence amplitude
measured on a <10μs timescale



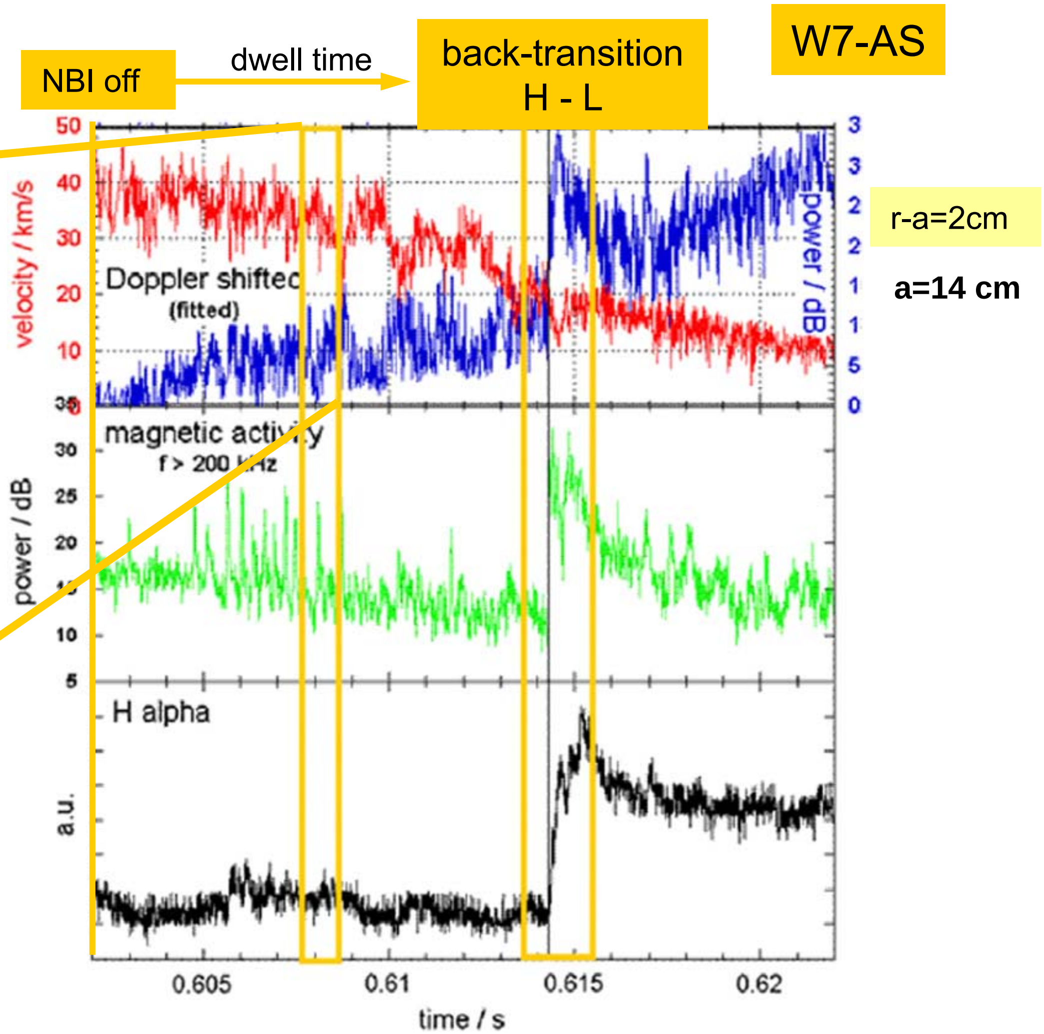
TJ-II

related observations
see talk. T. Estrada today

dynamics of turbulence and flows (zoom)



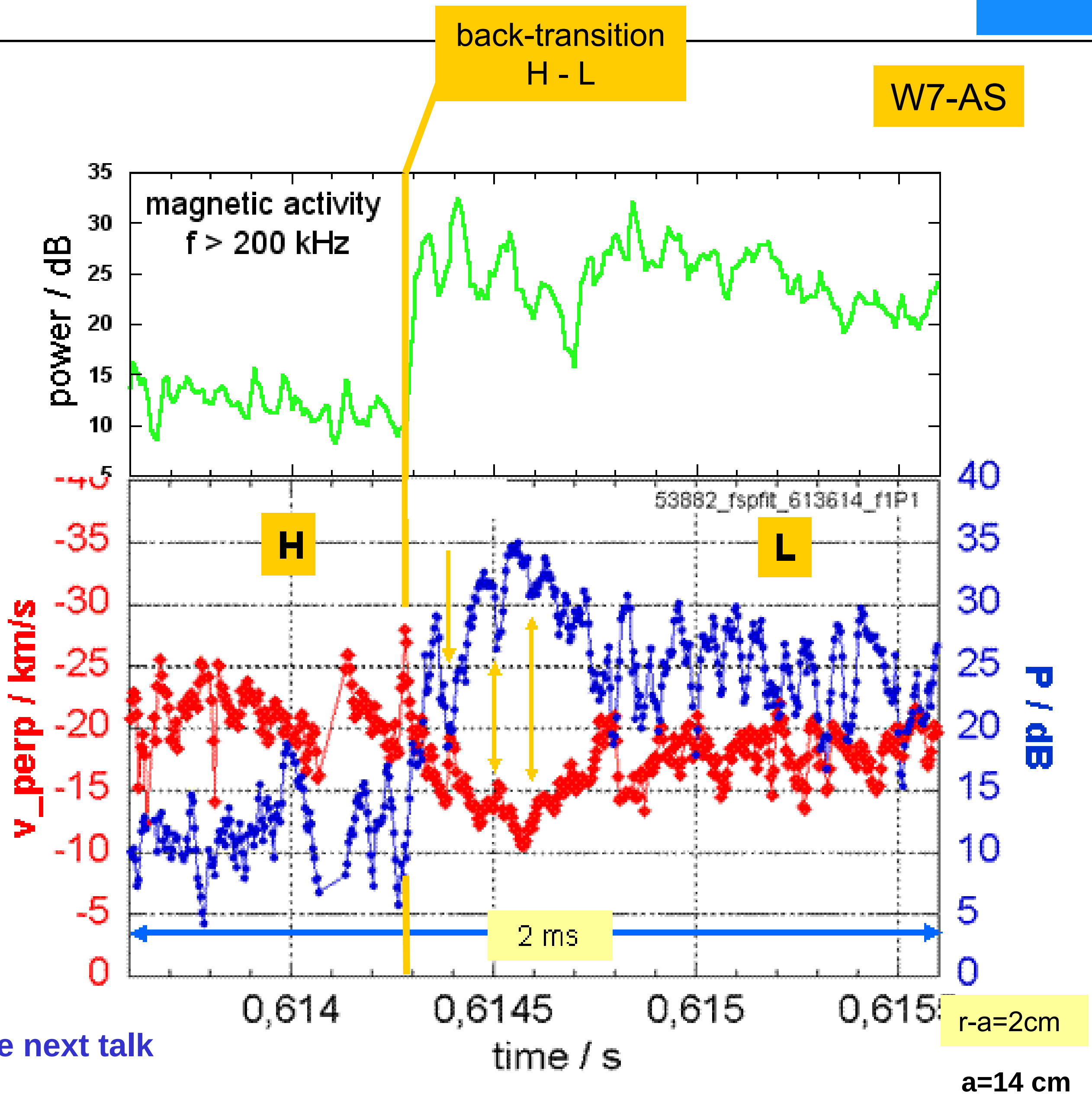
each data (4 μs) obtained from fit to microwave spectrum



-> turbulence amplitude and the poloidal propagaTion velocity show correlated oscillations
-> zonal flows ?

addressing causality: close-up to the H-L transition

transition timescale :
small scale f> 200 kHz
magnetic fluctuations
resond on **<40 µs timescale**



note:
the decisive local quantity is the shear of the turbulence propagation velocity !

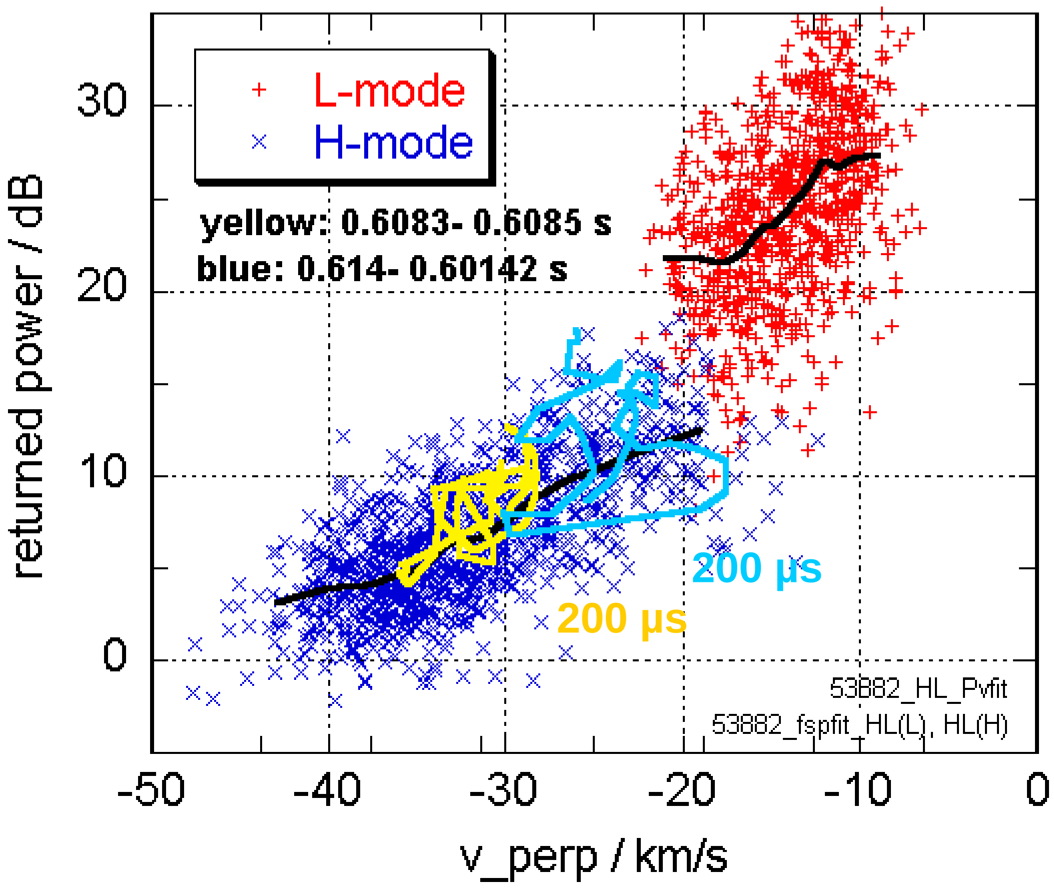
NOT

grad(Er)

-> related results from TJ-II see next talk

High- and Low-rotation branch of turbulence

W7-AS



There is no gap in v_perp betwen L and H branch in contrast to the 80 V/cm jump in Er observed from spectroscopy (but on a ms timescale there !).

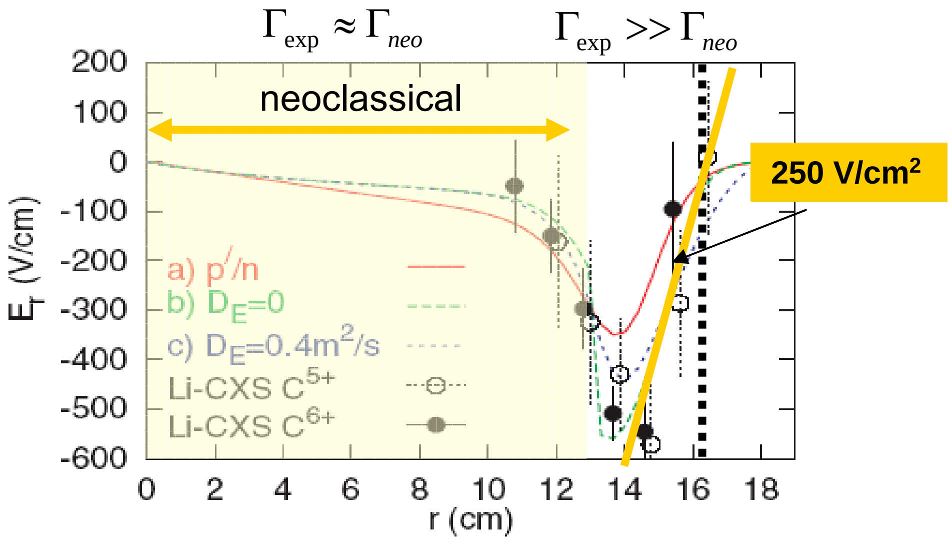
picture:
fluctuating / oscillating flow structures on top of the developing mean shear flow as the trigger for the transition between the **H**igh-rotation- and the **L**ow-rotation state of the plasma edge

the classical H-mode on a stellarator-edge background: - can already neoclassical E_r reduce turbulence ?

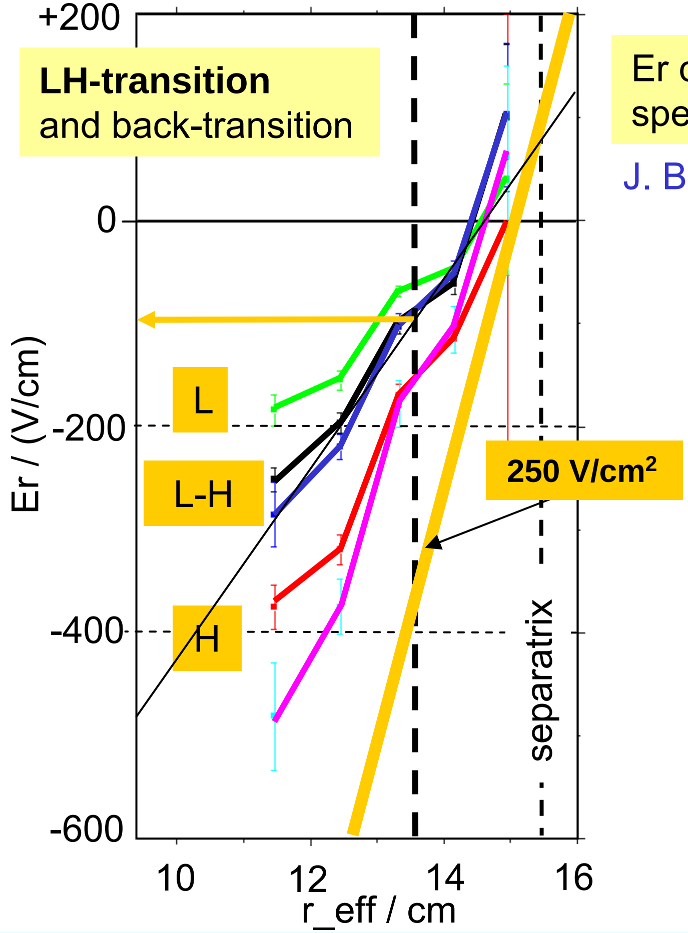
W7-AS

standard ion-root good confinement (OC-regime)
no abrupt transition, moderate turbulence

$$E_r \cong \frac{T_i}{e} \cdot \left[\frac{n'}{n} + \frac{D_{21}}{D_{11}} \cdot \frac{T_i'}{T_i} \right]$$



$$E_r^{exp} \cong E_r^{neo} + \delta$$



Er derived from spectroscopy

J. Baldzuhn

-> already **standard "good" confinement** reaches shear flow values like those or even exceeding those of the LH transition. No bifurcation is observed instead the turbulence amplitude reduces moderately as the profiles develop.

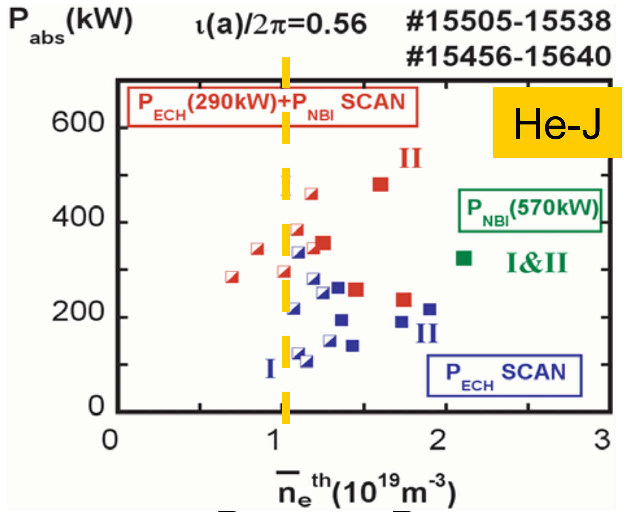
-> the **classical H-mode** is a bifurcation phenomenon *on top* of this mean shear flow conditions of the plasma edge which in helical devices is determined by the standard ion-root conditions

3) ETB operational space: thresholds in power and density (?)

He-J -> min Power required, density threshold
(indep. on iota_a ?) indep on power.

TJ-II -> high density - "at transition absorbed power is about that expected from tokamk threshold ..".

W7-AS -> high density, density threshold to H*-mode.



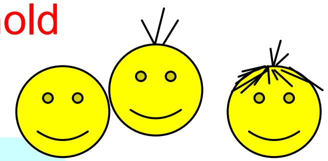
$P_{th\_HJ} << P_{th\_tok}$

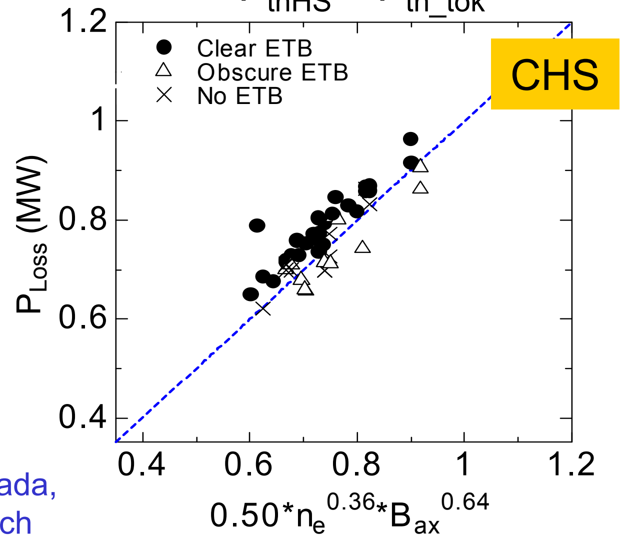
Density threshold

$P_{thHS} > P_{th\_tok}$

CHS ->Similar dependences on ne & Bt
like tokamak power scaling
Pthr > factor 2-3 higher than ITER H-mode threshold

LHD -> density window 4-8 10^{19} m^{-3}
power window, triggered by P reduction
Pthr > 1-2 times ITER H-mode threshold





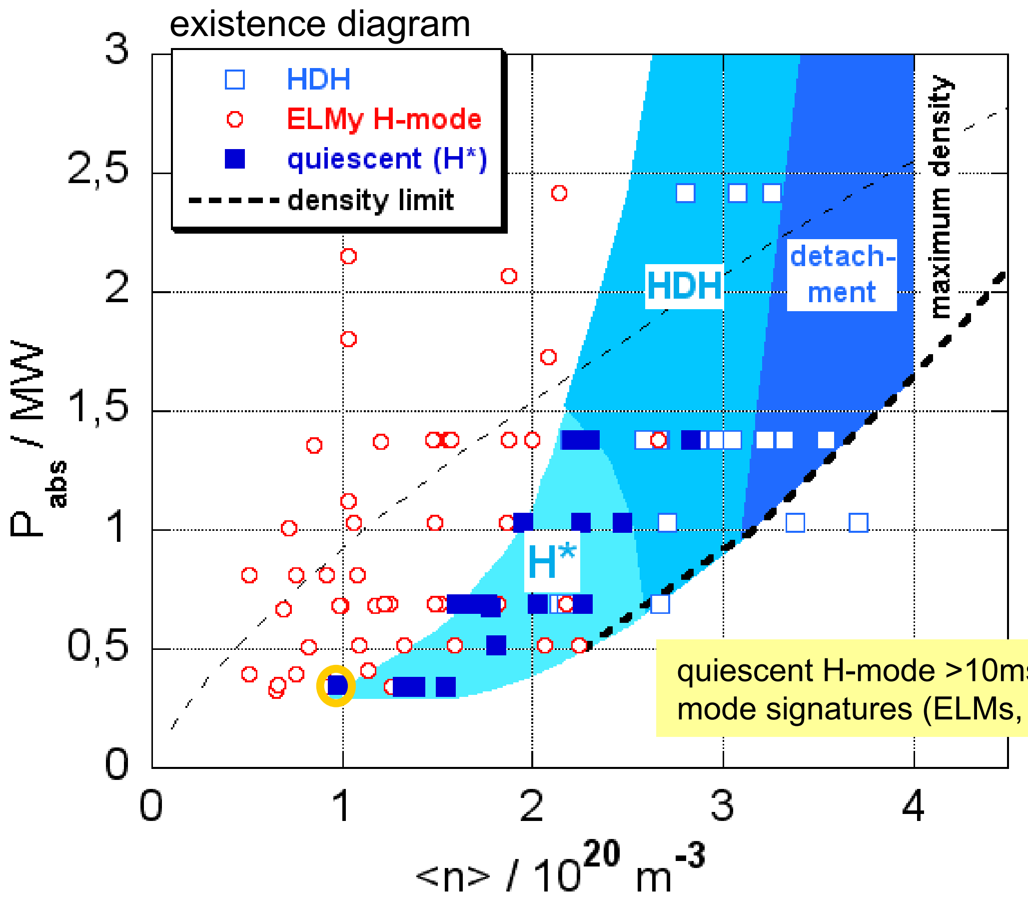
-> Coordinated Working Group established,
-> see poster Akiyama et al. Tue afternoon

T Akijyama, T Estrada,
T Mizuuchi, M Hirsch

operational space: comparison with Tokamak power threshold

W7-AS

operational space and ELM activity for
configuration 5/9 island divertor configuration



density limit scaling

quiescent H-mode >10ms already with reduced power and H-mode signatures (ELMs, short H* phases) early in discharge

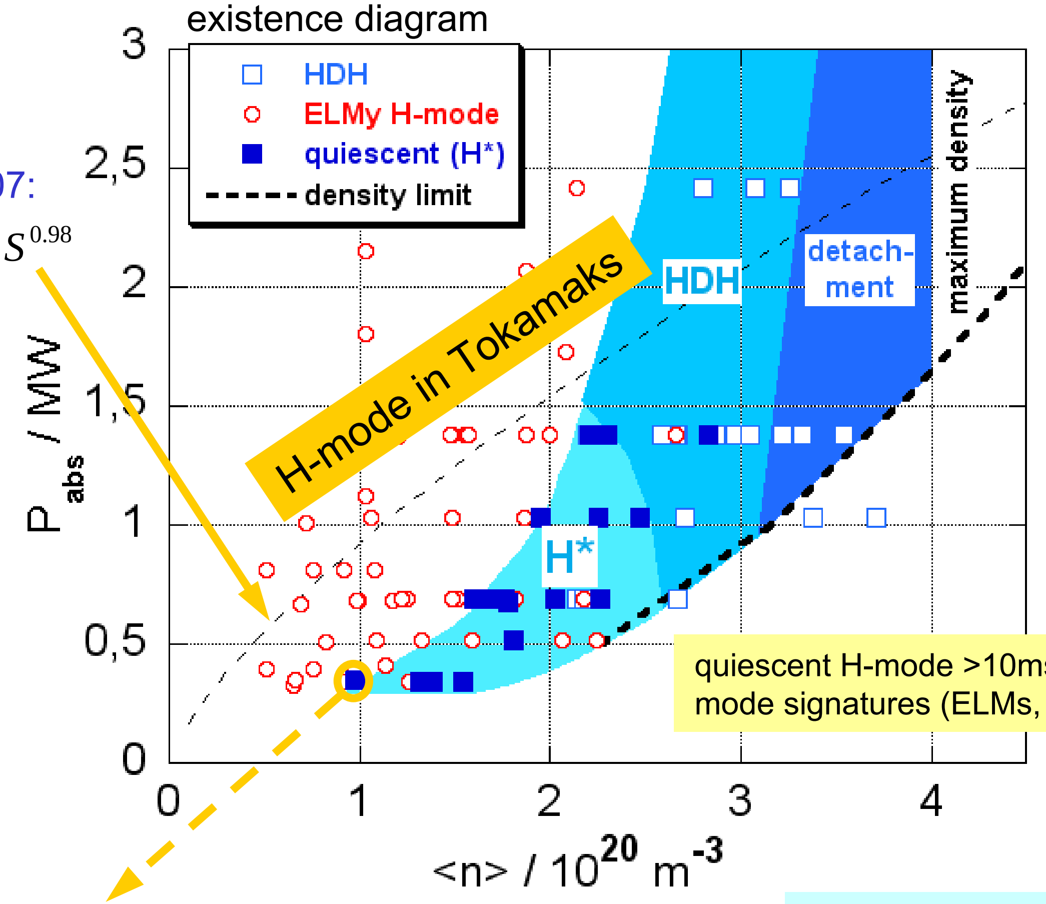
operational space: comparison with Tokamak power threshold

W7-AS

operational space and ELM activity for configuration 5/9 island divertor configuration

ITER physics basis 2007:

$$P_{thr} = 0.042 \cdot \overline{n}^{0.73} \cdot B^{0.74} \cdot S^{0.98}$$



density limit scaling

quiescent H-mode >10ms already with reduced power and H-mode signatures (ELMs, short H* phases) early in discharge

-> H* obtained with power significantly below tokamak H-mode threshold ("configuration biased H-mode")

(-> threshold behaviour inverse to tokamaks ?? "power must be *lower* than certain threshold ??")

more H-mode / ETB regimes:
e.g. W7-AS : **O**ptimum **C**onfinement and **H**igh **D**ensity **H**-mode

OC-regime
(various configs.)

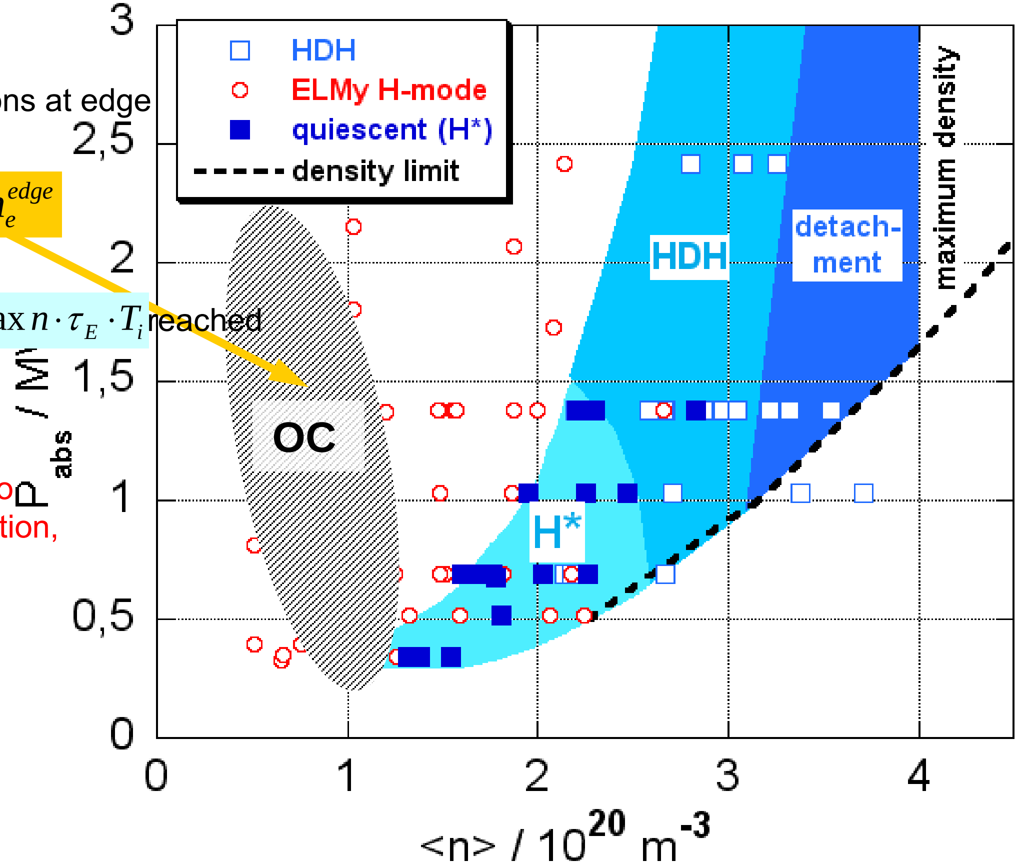
low needge (low recycling)
= maximum $grad(n)$ inside LCFS
+ good ion heating -> high $grad(T_i)$ at edge

strong negative E_r
widely explained
by robust ion-root conditions at edge

low n_e^{edge}

=> $\max T_e$ $\max \tau_E$ $\max n \cdot \tau_E \cdot T_i$ reached

-> ELM-like events but no
bifurcation, no fast transition,
no back transition



more H-mode / ETB regimes:
e.g. W7-AS : Optimum Confinement and High Density H-mode

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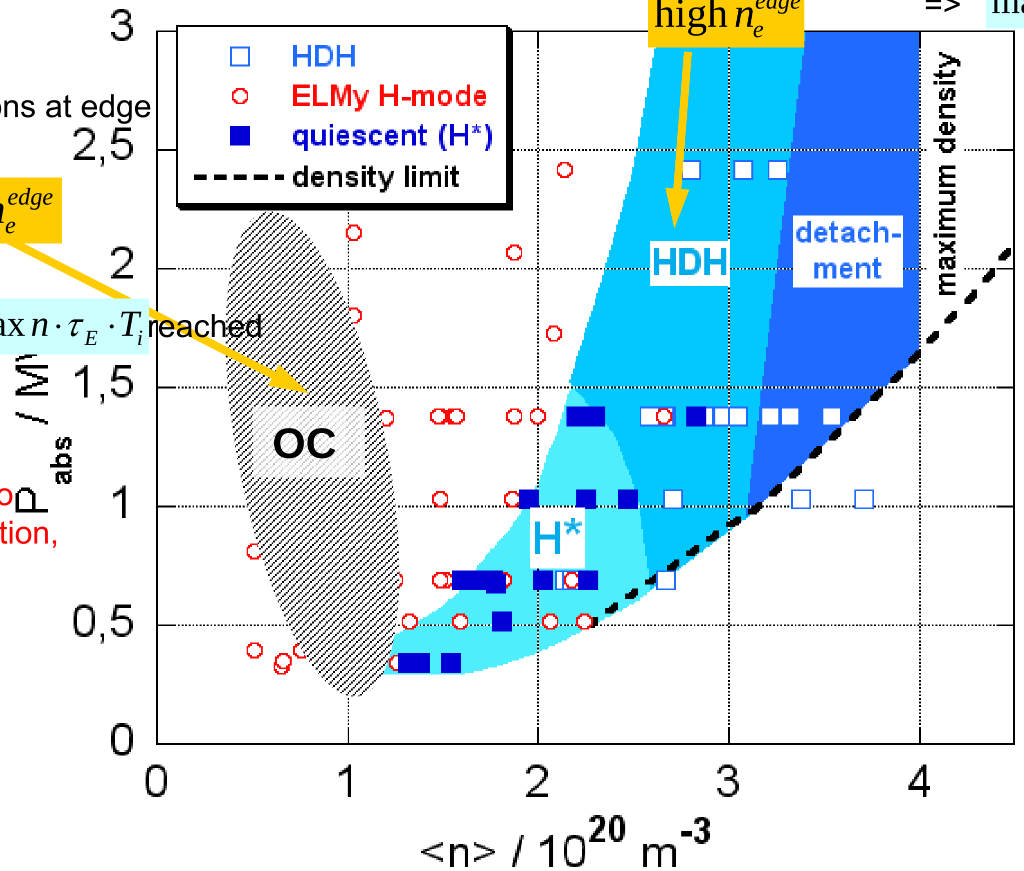
HDH-regime (various configs.)

less sensitive on configuration than H-mode
max grad(ne) at or even outside LCFS
-> poor impurity confinement
=> $\max \beta$ $\max n_e$

high n_e^{edge}



transitions possible:
H*->HDH
H*->OC
(OC -> ELMy -> H*)

more H-mode / ETB regimes:
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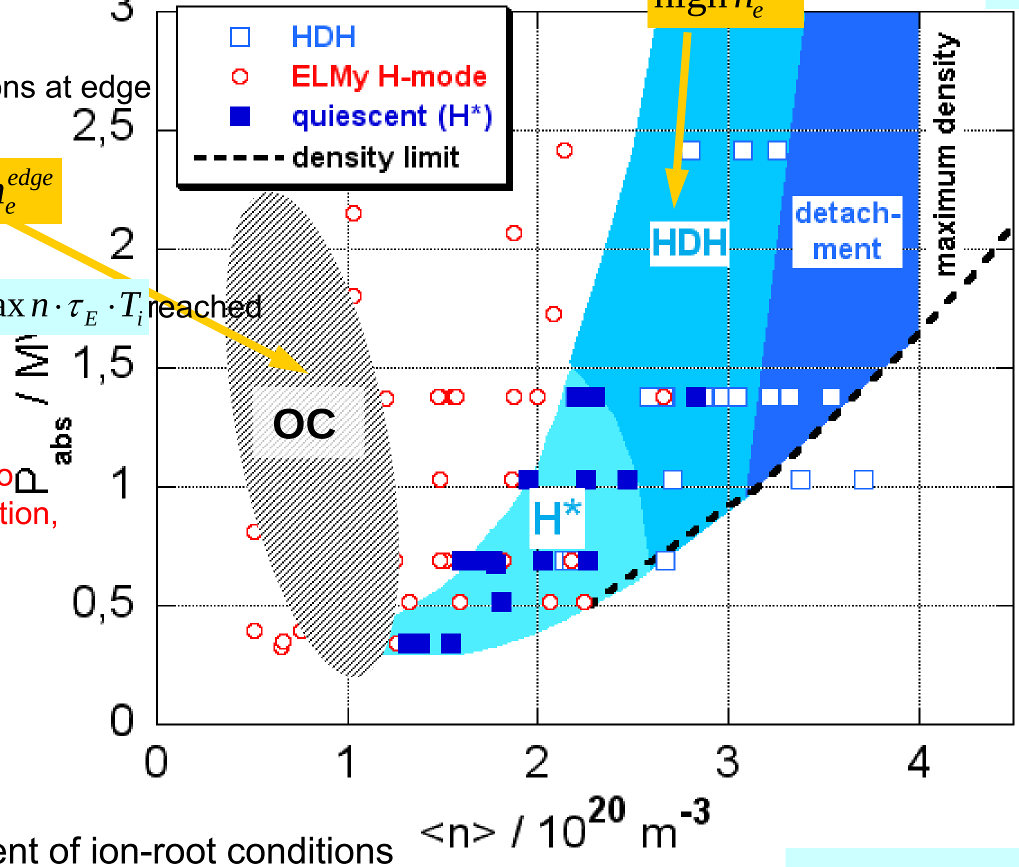


transitions possible:
H*->HDH
H*->OC
(OC -> ELMy -> H*)

TJ-II -> establishment of ion-root conditions (negative Er) already early in the discharge already at lower ne ? **-> Pedrosa talk this morning**

-> other ETB states exist on top of robust *ion-root conditions* at edge

CHS ? -> two step transition

summay: characteristics of the H-mode in helical devices

The **classical (quiescent and ELMy) H-mode** is close the references from Tokamaks

In **helical devices pecularities exist** with respect to operational range:

-> configuration (iota)-dependence, influence of rationals and ergodization

-> role of (neoclassical) equilibrium E_r (ion-root) as a bias with impact on P-threshold (?)

other ETB regimes, "H-modes" are possible:

W7-AS -> low ne_edge, achieved by low recycling, deep fuelling, large fraction with high T_i
described by neoclassics: **Optimized Confinement**
-> high ne_edge, achieved by strong external gas feed, reduced impurity confinement:
High-Density-H-mode (HDH)

TJ-II -> low density transition to sheared flow

CHS -> **limiter H-mode**, two-step transition

....

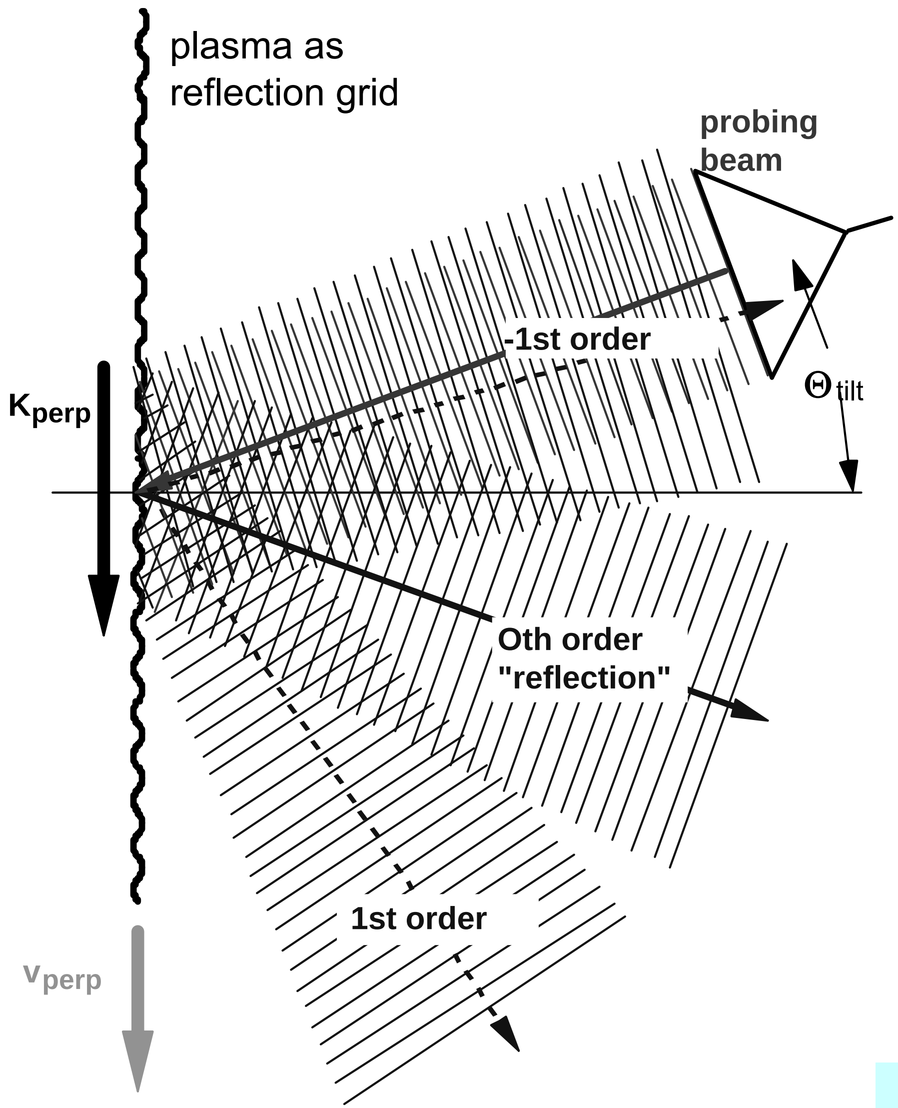
Working Hypothesis:

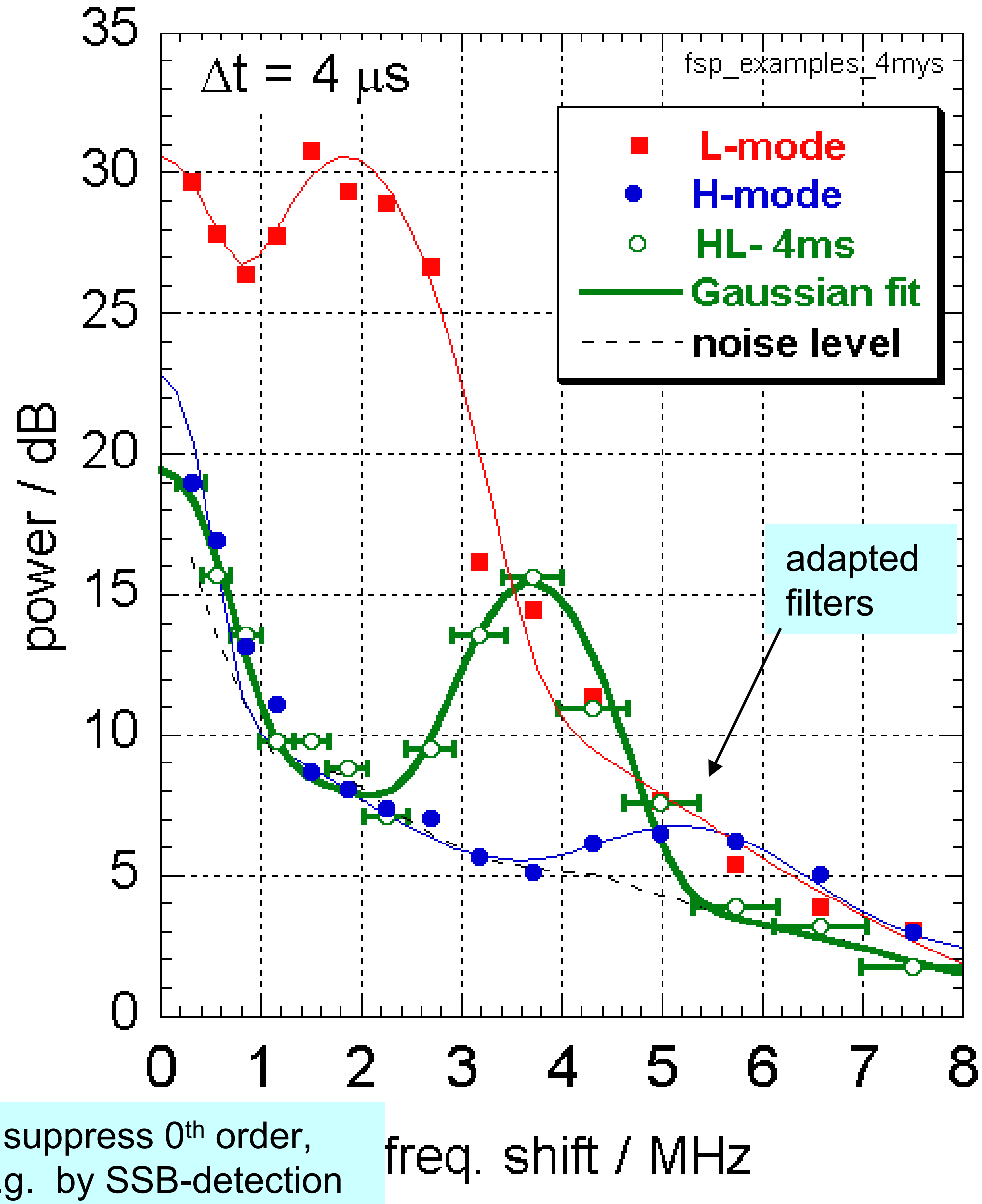
Consider the **classical H-mode** as fast **bifurcation** of turbulence, and **dynamic sheared flows on top of** and possibly **biased** by the **equilibrium conditions of the stellarator edge**.

... a "configuration biased" H-mode ?

The stellarator edge may transit to other improved confinement states on a transport timescale, e.g. dominated by the **mean shear flow** and thus without fast bifurcation.

principle of Doppler reflectometry



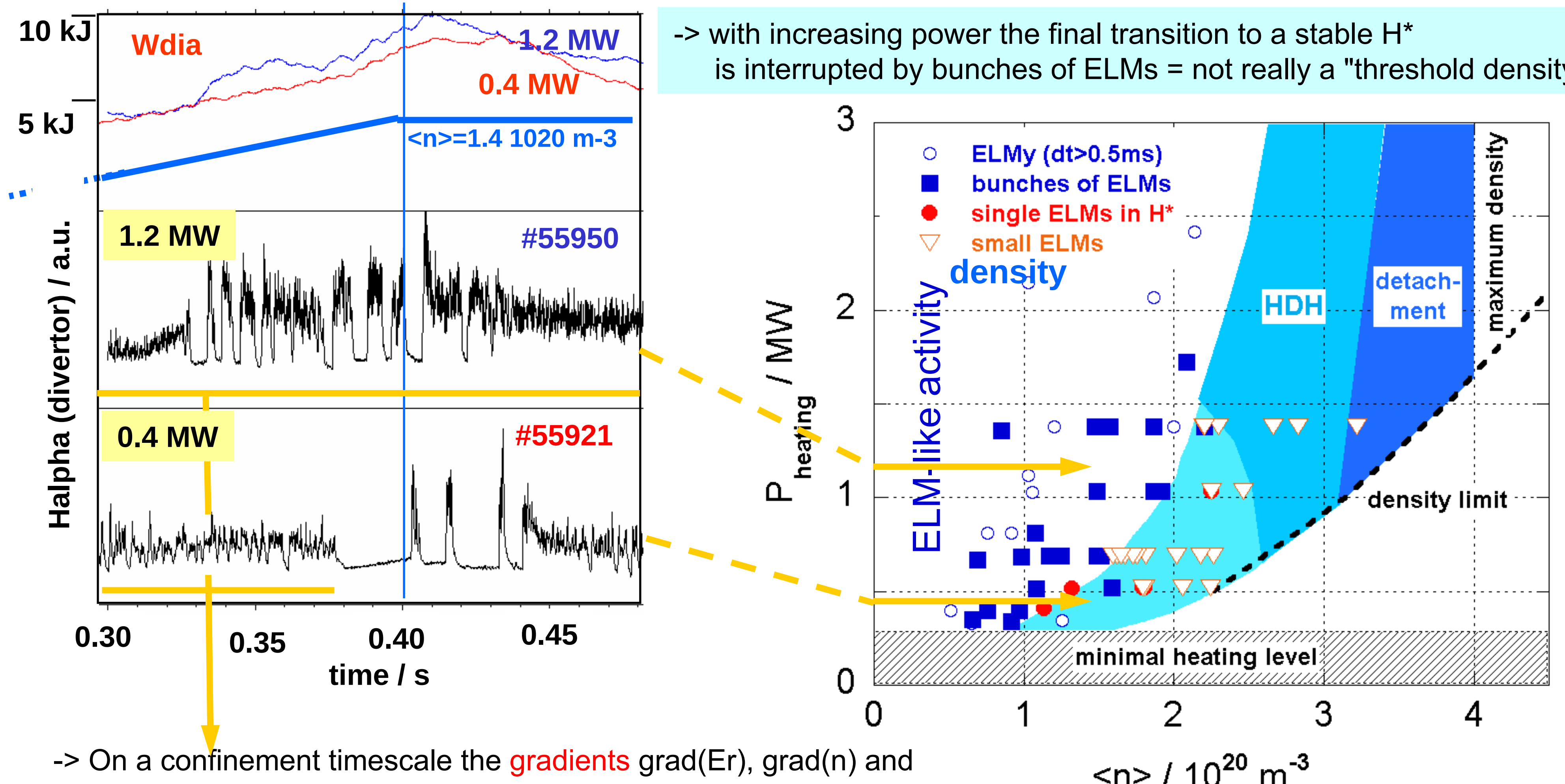


suppress 0^{th} order,
e.g. by SSB-detection

operatioal space: a density threshold ?

W7-AS

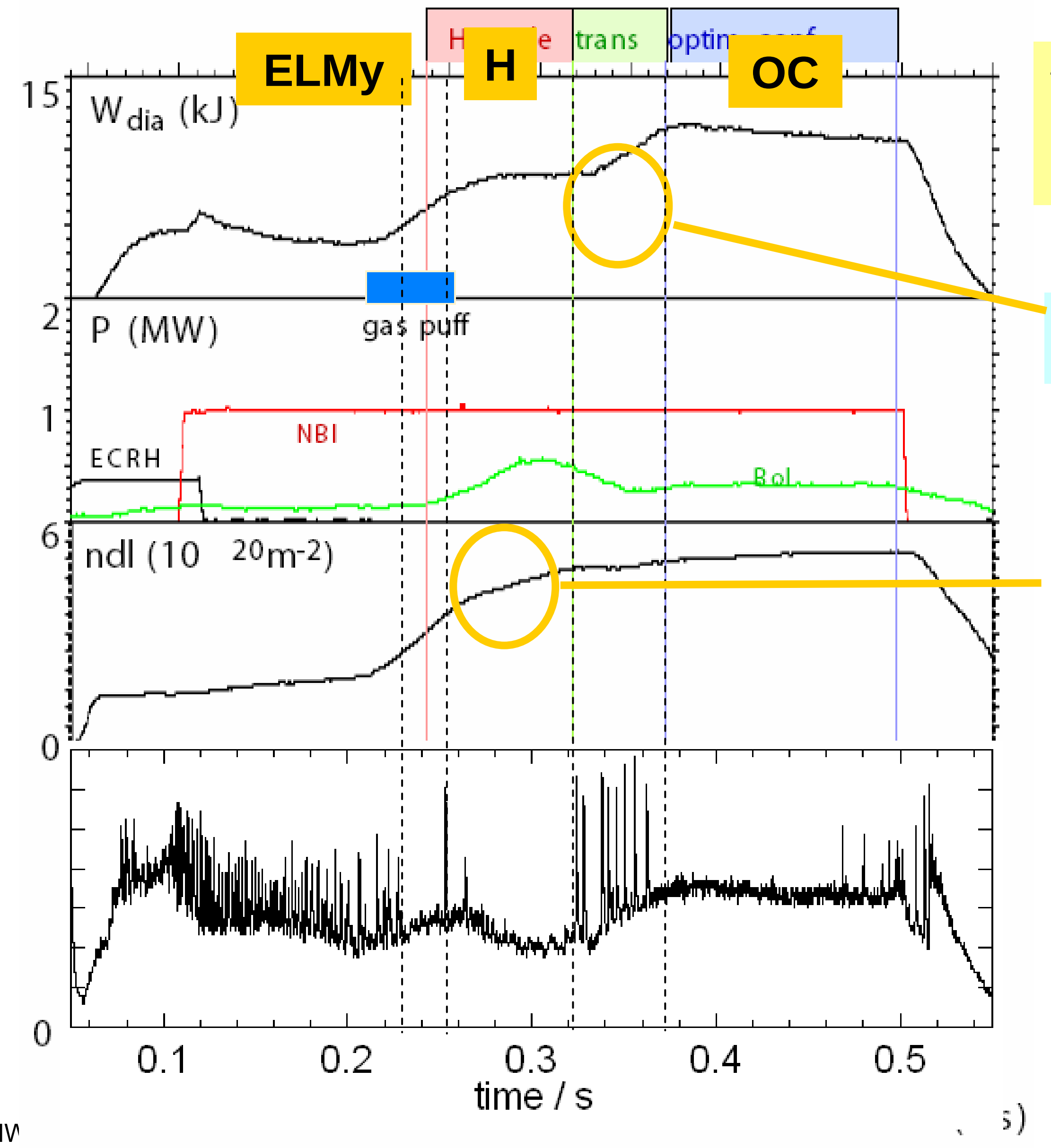
-> with increasing power the final transition to a stable H*
is interrupted by bunches of ELMs = not really a "threshold density"



-> On a confinement timescale the gradients grad(Er), grad(n) and grad(Ti) steepen in parallel with the disappearance of ELMs bunches.

-> The energy confinement time exceeds the values from the ISS already during the phase preceeding the quiescent H-mode.

transformation from H* -> Optimum Confinement (maximum Ti)
... by reduced gas flux (no gas puff)



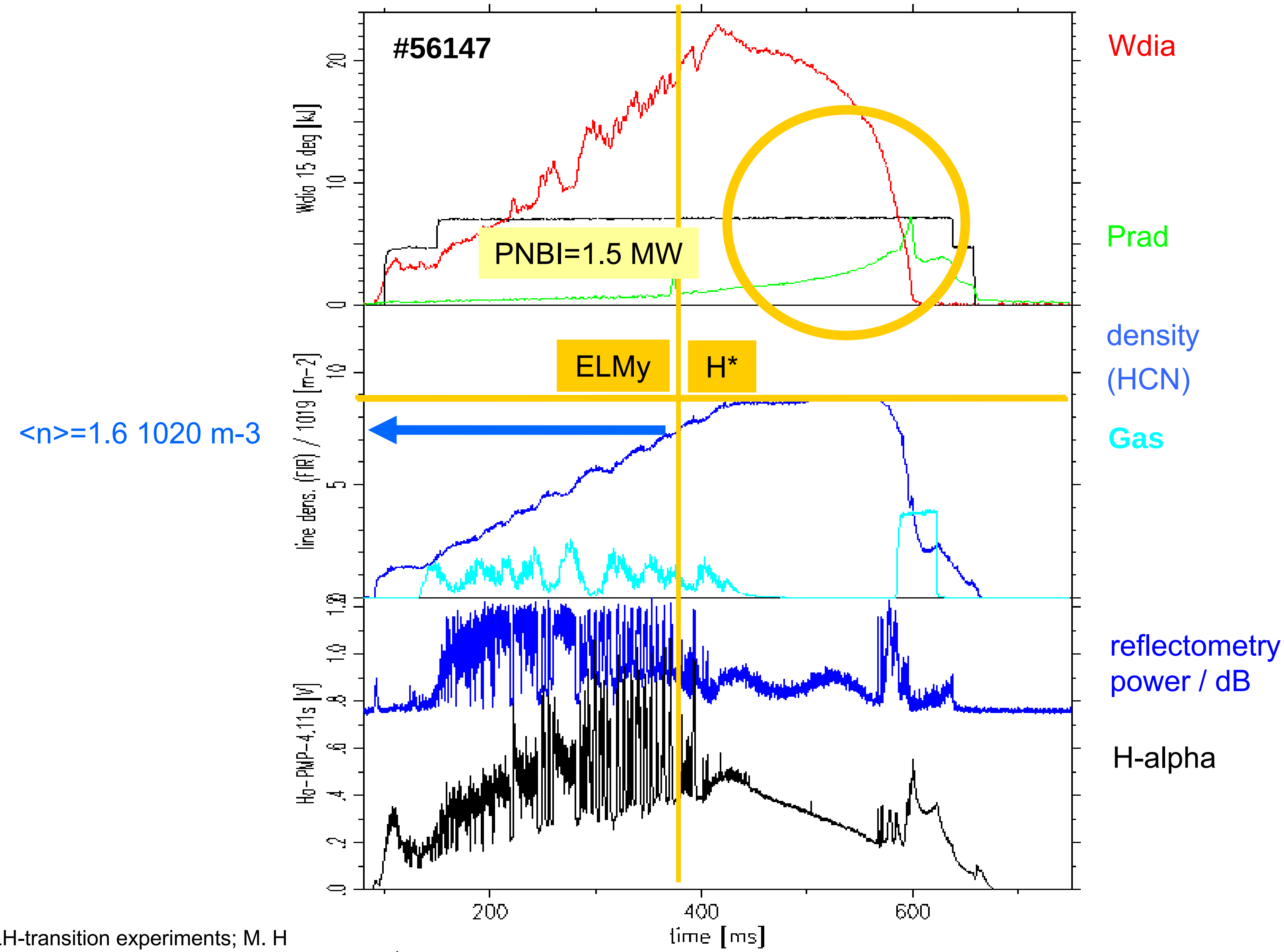
#43643: H* to OC: Kick et al EPS
Pabs=0.7MW (2NBI), iotaa=0.525,
n(->H*)=4.2 1019 m-3
n(-> OC)=9.6 1019 m-3

narrowing of n-profile becomes possible as external gas puff has been stopped

gas feed by NBI only

H-mode analogon with neoclassical Er ?

classical H-mode reached by density ramp
... is terminated by radiation



transformation from H -> stationary High Density H-mode
... by strong gas puff

H-mode
with Er / shear flow
decorrelation ?

<n>=1.6 1020 m-3