High Performance Regimes on Wendelstein 7-AS
- Essential Elements of the High Density H-Mode -

Kent McCormick for the W7-AS and NBI Teams

The HDH-Mode was the workhorse of the divertor phase
=> many talks involving aspects of HDH <=

W7-AS Summary:	R. Jaenicke... Monday 09:00
W7-AS Fluctuations in H*-HDH:	S. Bäumel... P.Mo12
W7-AS Operational Access to HDH	Y. Igitkhanvov...P.Mo2
W7-AS & Other Divertor Experiments:	R. König... Tuesday 10:15
W7-AS Divertor Experiments:	P. Grigull... Thursday 11:15
W7-AS Impurity Transport:	R. Burhenn ...Thursday 12:15
W7-AS 3D Edge Transport Calculations with EMC3:	Y. Feng... Friday 10:15

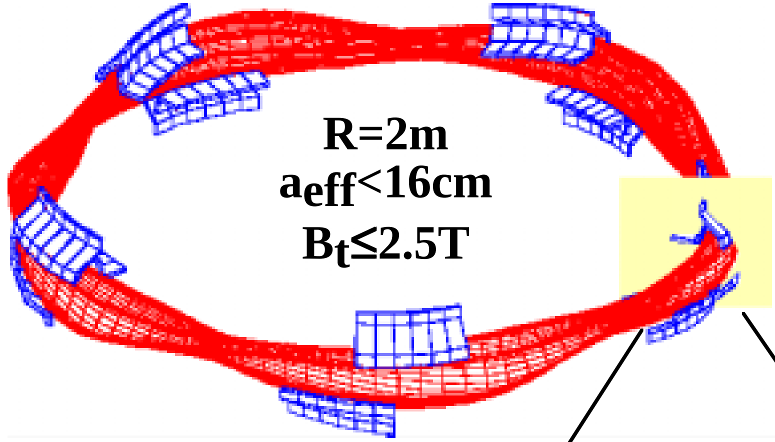
This talk will <u>attempt</u> to illuminate the essence of the HDH-Mode:
- **nature of the transition to HDH** — NC->HDH
- **characteristics of "Normal Confinement" vs. HDH** — NC vs. HDH
- **expts. to elucidate "impurity-flushing" features of HDH** — HDH/H*
- **comparison to ELM-free H-modes in tokamaks** — EDA vs. HDH
- **outlook**

The High Density H-Mode in Wendelstein 7-AS
- history -

Operation with Divertor Modules over April 2001 - July 2002

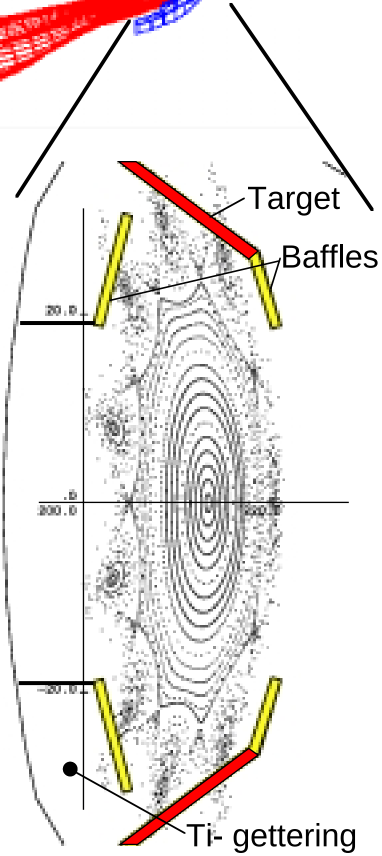
High Density H-Mode (HDH) Discovered & Exploited

W7-AS Ceased Operation July 31, 2002



P_{nbi}≤ 3MW
V~0.7-1 m^3

carbon target plates stainless walls



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The High Density H-Mode

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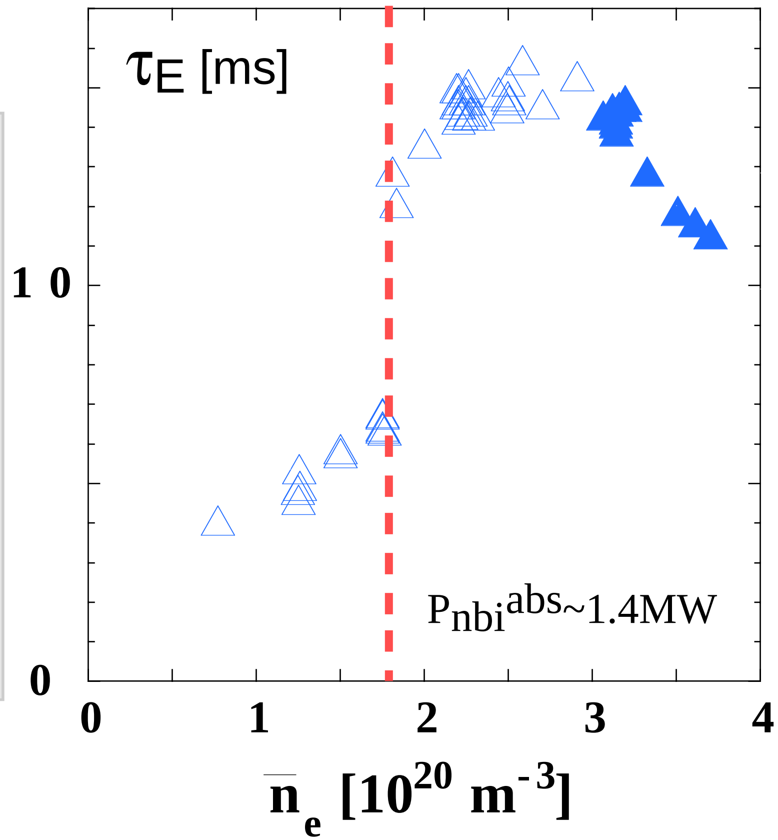
The HDH-Mode is a High Performance ELM-free H-Mode
It has enabled high-density island-divertor studies.

NC->HDH

Normal Confinement (NC) | High Density H-Mode (HDH)

at high ne
- poor density control
- impurity accumulation
- Prad in center
-> radiation collapse
-> transient

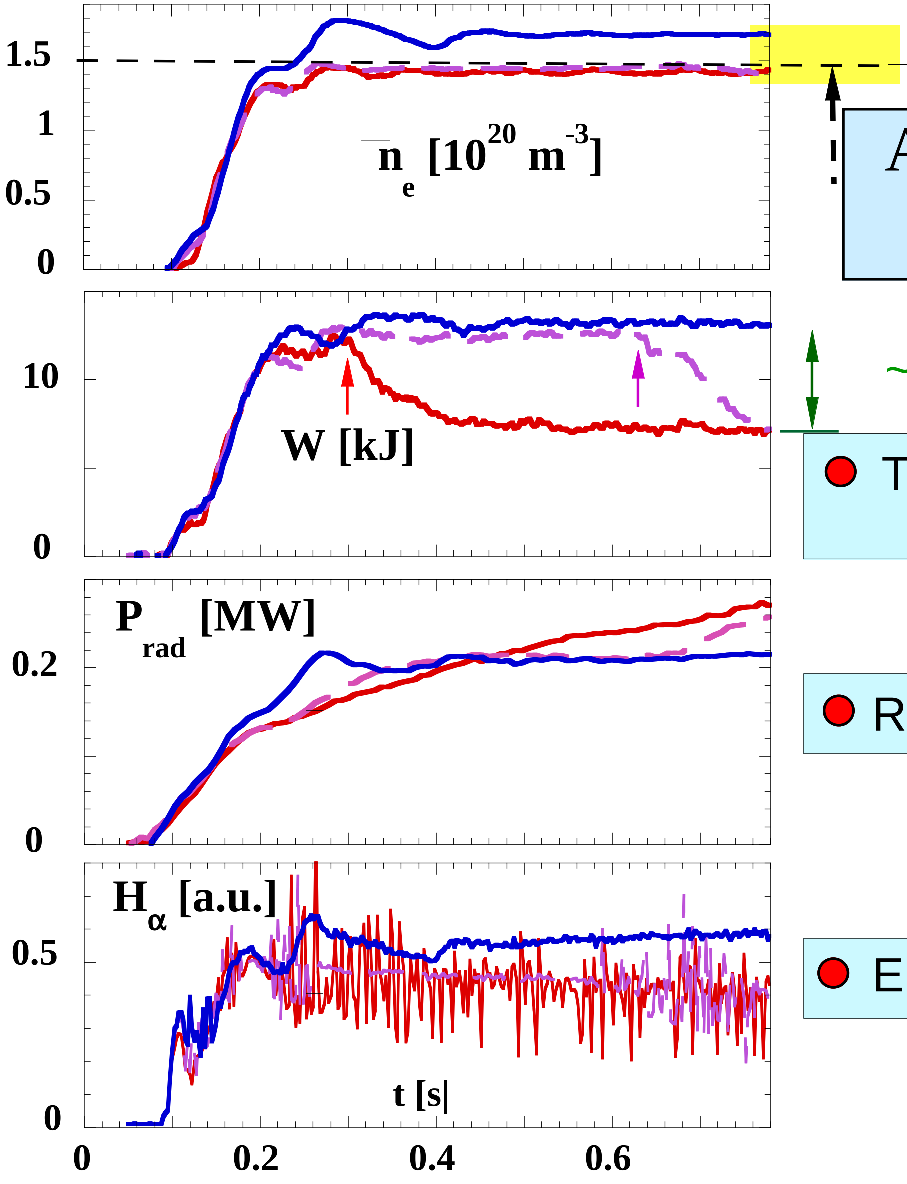
$\bar{n}_{e,max}$ ~ 2.5 10^{20} m^{-3}



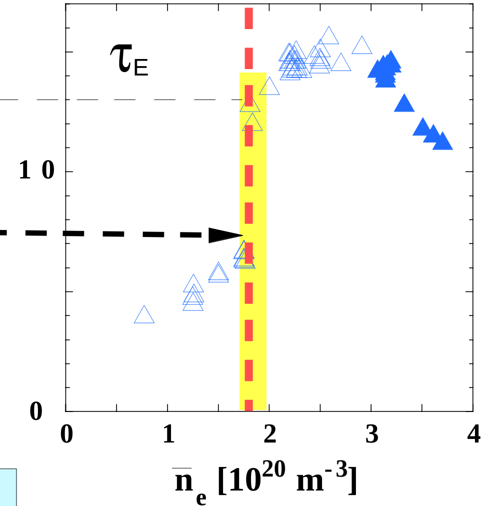
above n_e^{thr}
- good density control
- no impurity accumulation
- high Prad at edge
- high energy confinement
- quasi-stationary

$\bar{n}_{e,max}$ ~ 4 10^{20} m^{-3}

Global Behavior: near HDH - NC transition density



NC->HDH



As the density threshold is approached:

~2x increase in stored energy

- The phase of high confinement becomes longer.
- Radiation remains stationary longer.
- ELMing decreases.

Normal/HDH-Confinement τ_E-plot

- considering non-stationary phase at beginning of discharge -

NC->HDH

below the n_e^{th} the gas puff

temporarily creates HDH-like profiles

-> with no ELMs

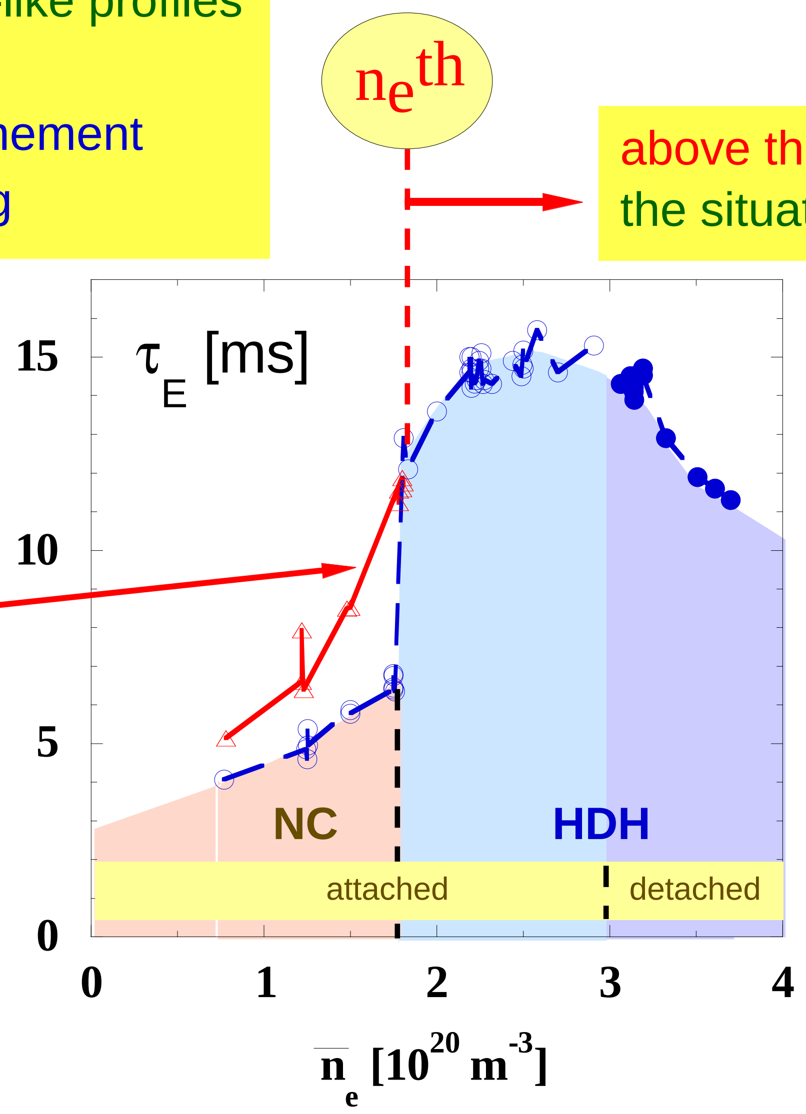
-> with high energy confinement

-> but no impurity flushing

above the n_e^{th}

the situation is self-sustaining

gas puff effect?



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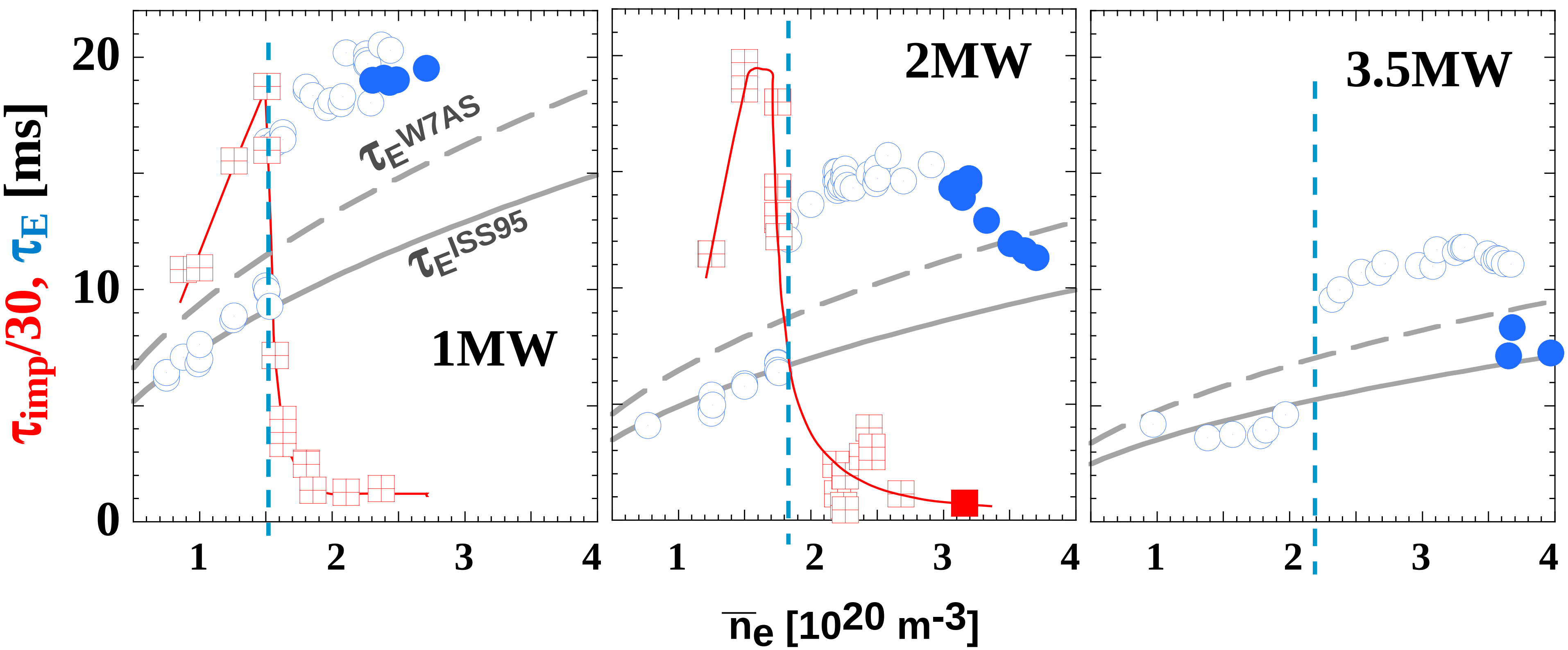
HDH Exists over a Wide Range of P_{nbi} & Density

τ_E and τ_{AI} vs. n_e (quasi-stationary discharges)



- The NC->HDH transition density increases with P_{nbi}
- τ_E increases sharply at the transition
- τ_{imp} decreases sharply at the transition, approaching τ_E at higher n_e
- τ_E is higher than conventional scalings in HDH-Mode

NC->HDH

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The H-Mode is Attained by Increasing the Density NOT the Power

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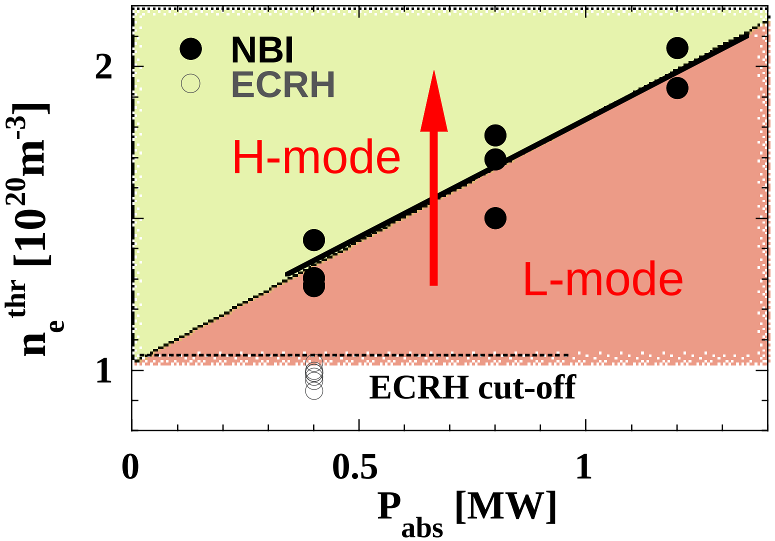


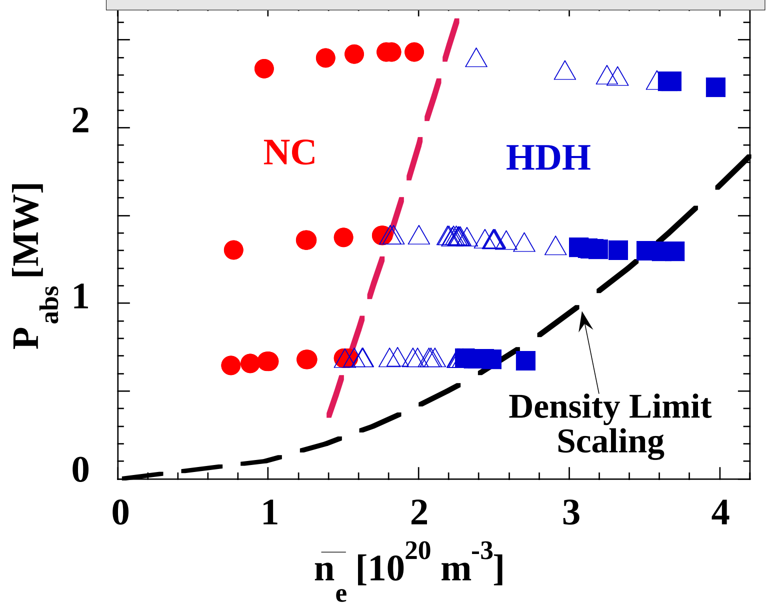
In contrast to tokamak scalings
- higher power is detrimental to the H-mode.

Related to strong τ_E density scaling?

$\tau_{LG} \sim 0.21\ (n_e/P)^{0.6}\ B_t^{0.8}\ a^2\ R\ \iota^{0.4}$

NC->HDH

NC - HDH Operational Diagram

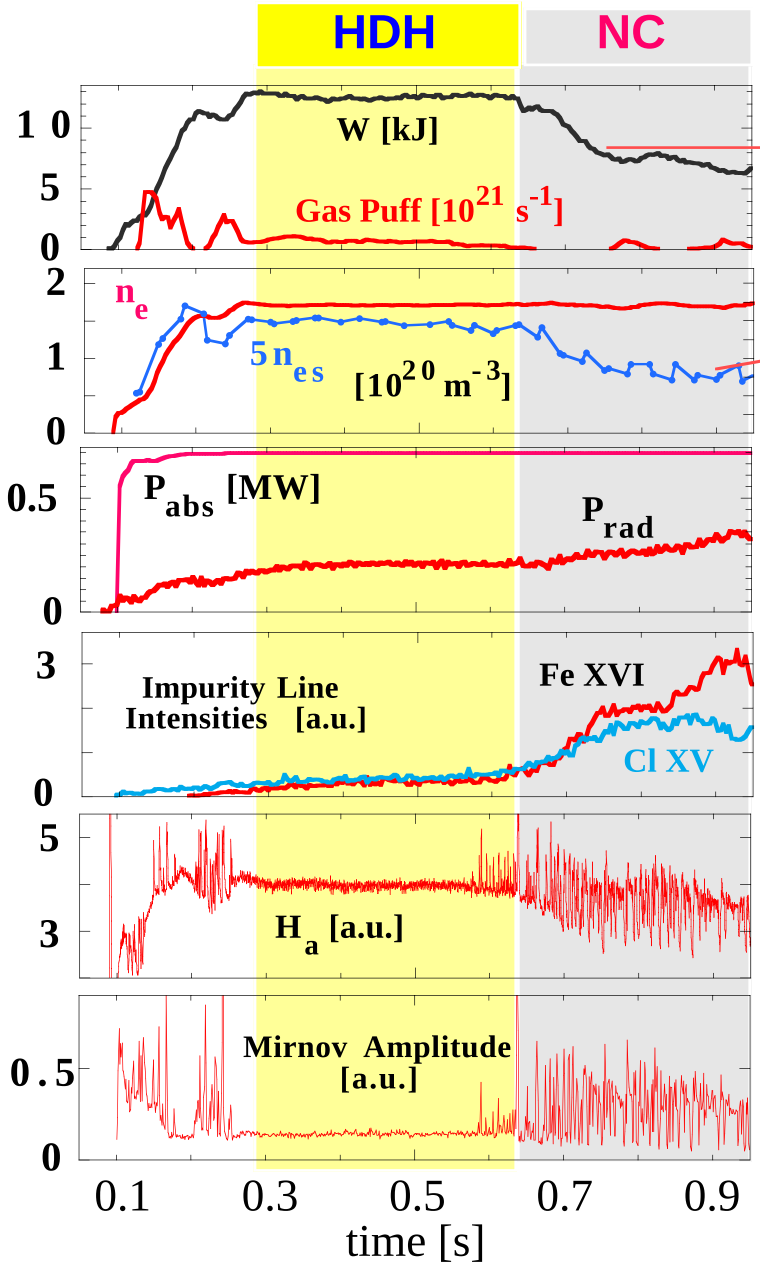


H^o -> H^+

$n_e^{DL} \sim 1.5\ (PB/V)^{0.5}$
(radiation limit)

Plasma Behavior for Density ≤ Threshold Density

Spontaneous Backtransition: HDH -> Normal Confinement



NC vs. HDH

Stored Energy is lower in NC

Separatrix density n_{es} is lower in NC
- for the same line-averaged density

P_{rad} increases in NC

Impurity line intensity increases in NC

HDH shows no evident ELM activity

HDH shows reduced MHD activity

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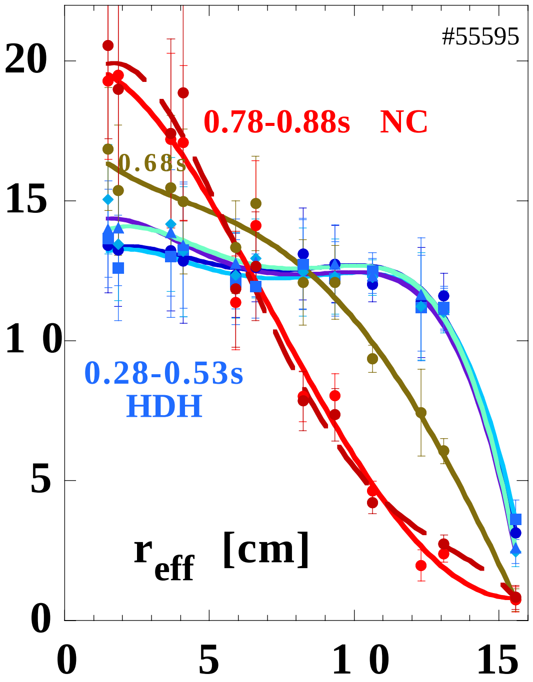
Profile Development

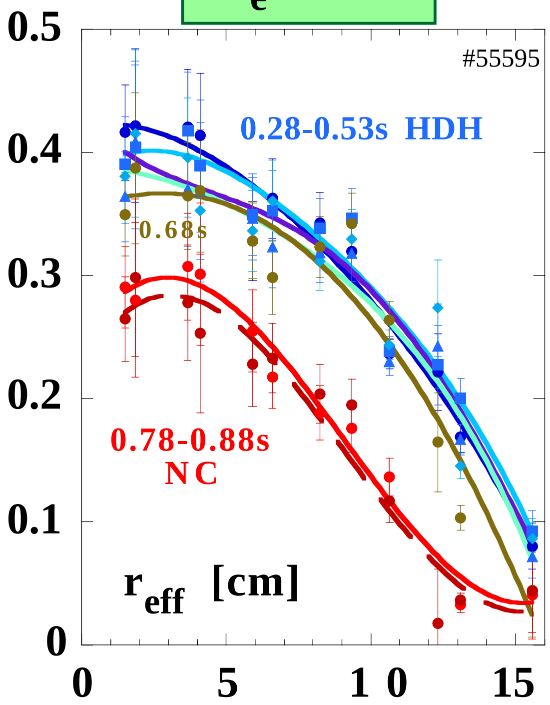
$n_e(r)$: Normal Confinement is Peaked, HDH is Flat

Density, Temperature & Radiation Profiles

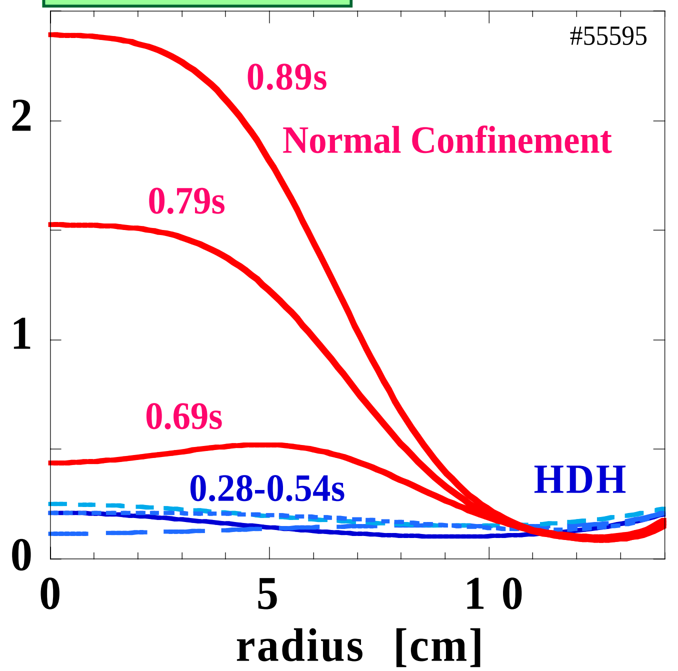
n_e [10^{19} m^{-3}]



T_e [keV]



P_{rad} [W m^{-3}]



	$n_e(r)$		$T_e(r)$	$P_{rad}(r)$
NC	peaked	NC vs. HDH	peaked	peaked, increasing
HDH	broad		peaked	hollow, stationary

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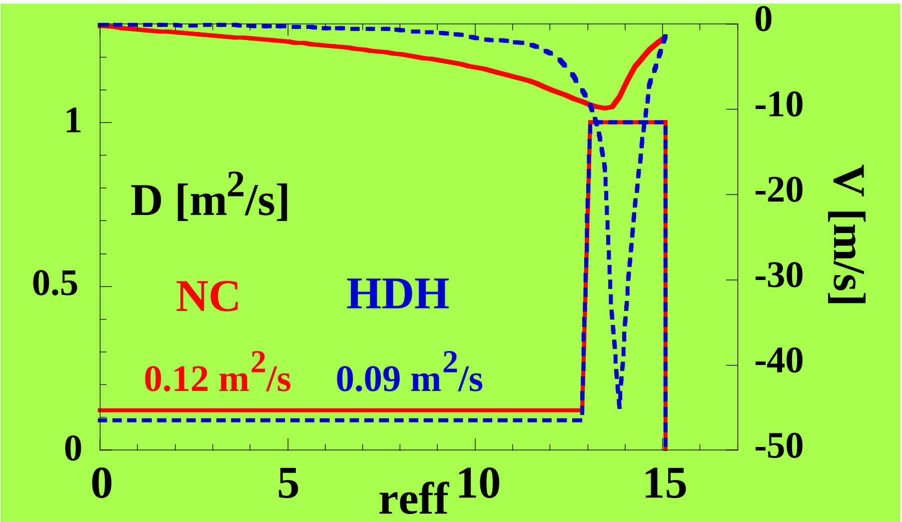
First Approach to Modeling τ_{Al} Behavior

(explain radical decrease in τ_{Al} for NC -> HDH)



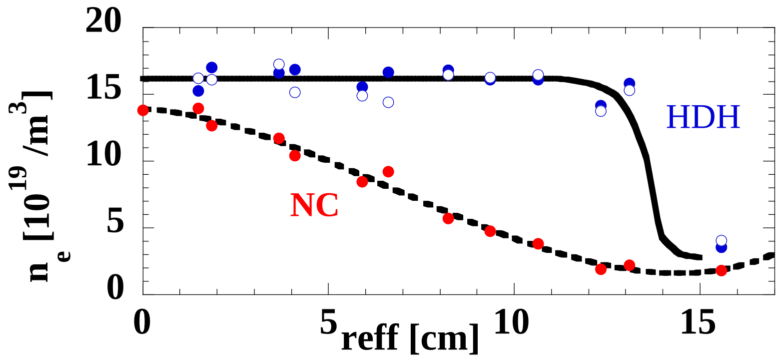
* Assume: v_{in} ~ (dp/dr)

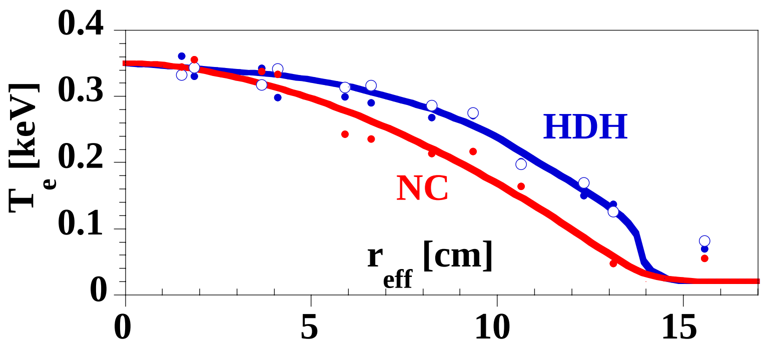
-> leads to a large inwards pinch in gradient

=> must assume large diffusion to counteract

- otherwise, D is chosen in core to match τ_{Al}

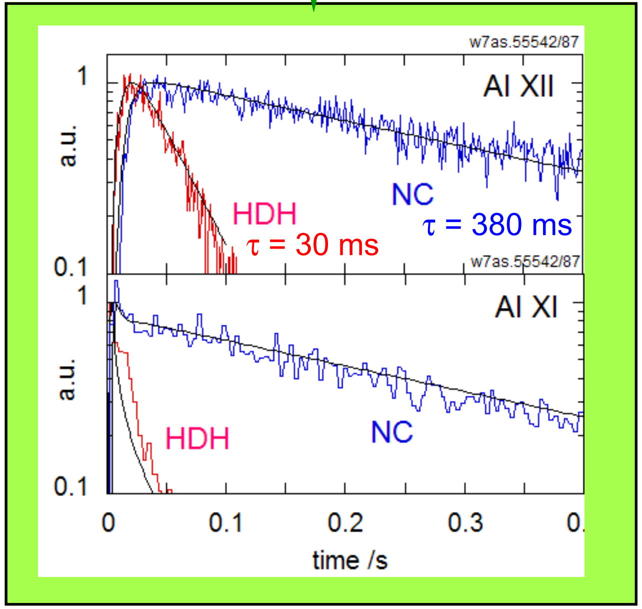
This model can simulate the Al-LBO traces well:





NC vs. HDH

HDH/H*



Burhenn
Ida

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HDH/H*

But life is not that simple

ELM-Free H-Modes (H*) also Exist on W7-AS

... which <u>suffer from Impurity Accumulation</u>

... with <u>otherwise similar global properties to HDH</u>

A Discharge has been Tailored to Study H* and HDH under the same conditions of heating and magnetic configuration ...for which a higher density is required to attain HDH:

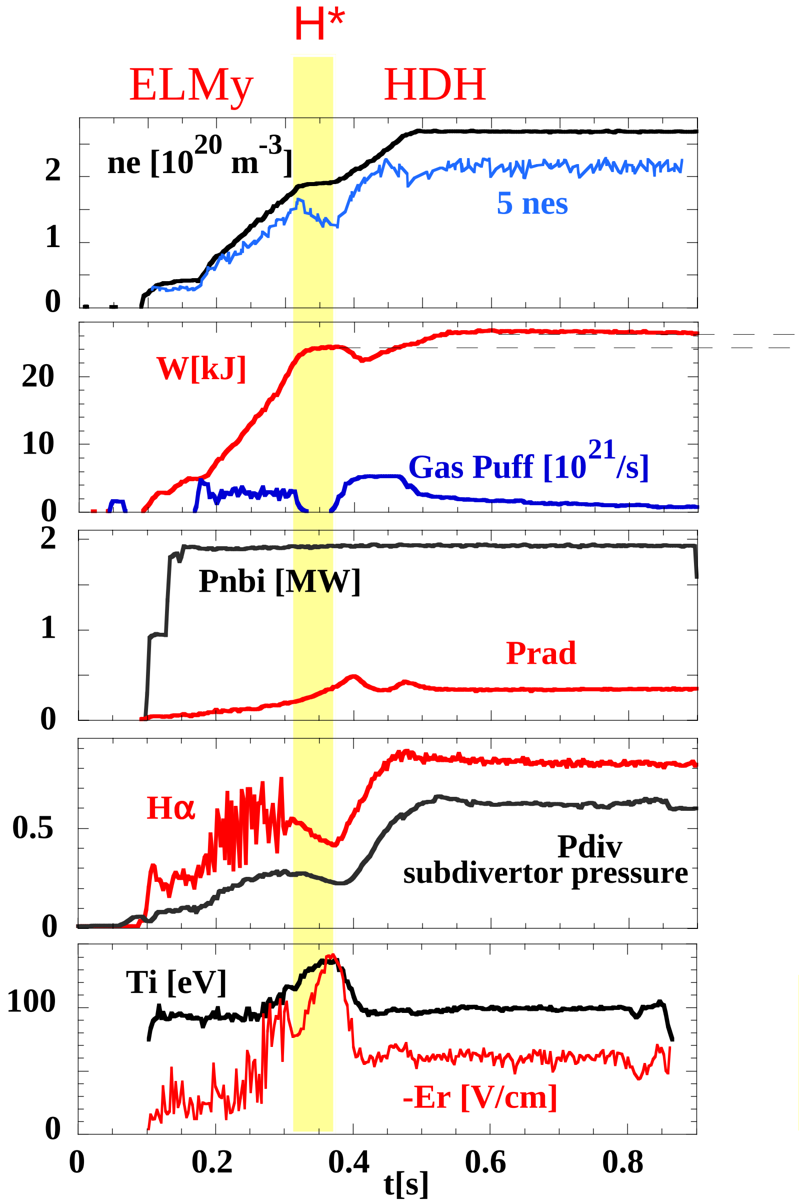
At beginning of discharge, under influence of gas puff even for $n_e < n_e^{th}$

ELM-Free H-Mode exists temporarily

which also exhibits P_{rad} increase

H* (impurity accumulation) & HDH (impurity flushing)

Pnbi = 2MW



HDH/H*

n_e ramp to H*...flat...then ramp to HDH

separatrix density n_{es} more-or-less follows n_e

little difference in stored energy

=> higher n_e -> lower T_e

increasing P_{rad} in H*...P_{rad} constant in HDH

Both H* and HDH show no evident ELM activity in Hα

T_i and the radial electric field E_r are higher in H*

-> higher pressure gradient -> lower transport in H*?

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H*/HDH

H* & HDH

expanded time scale

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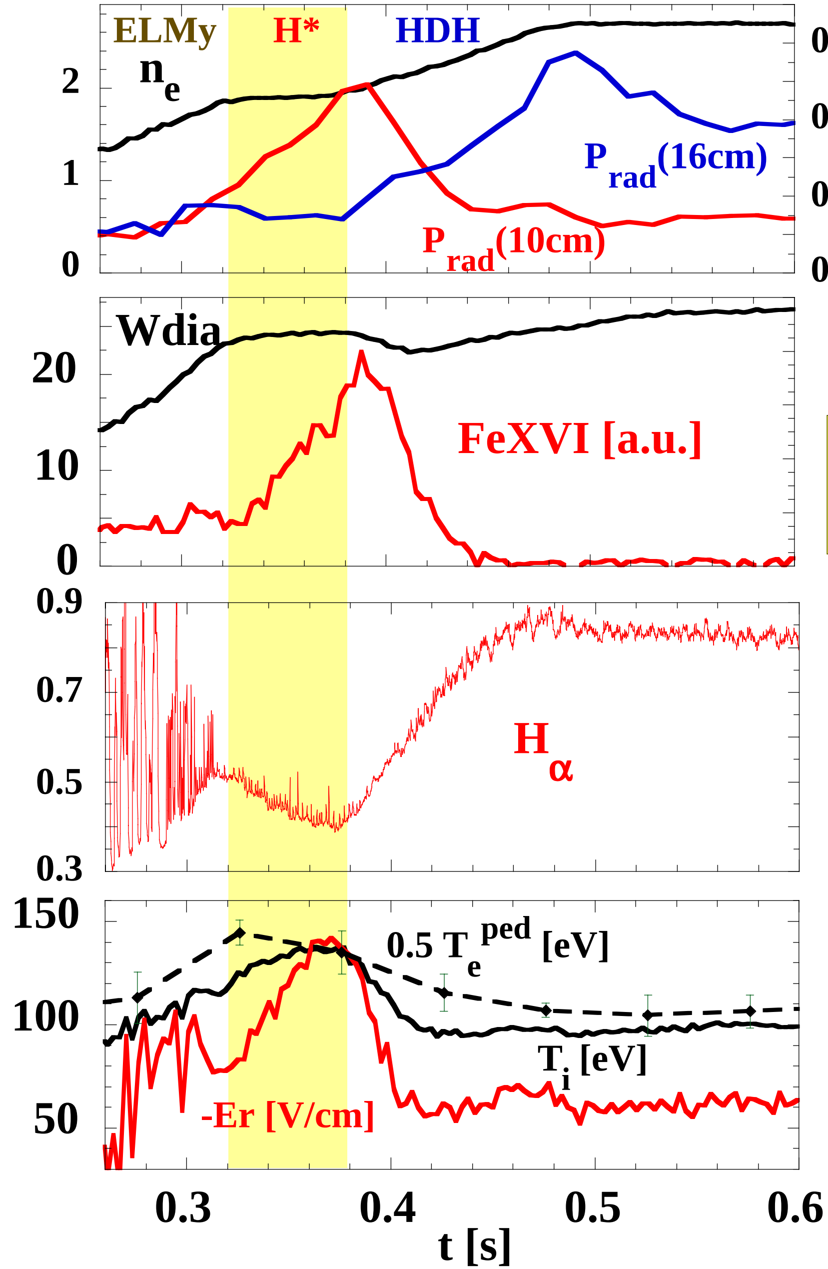
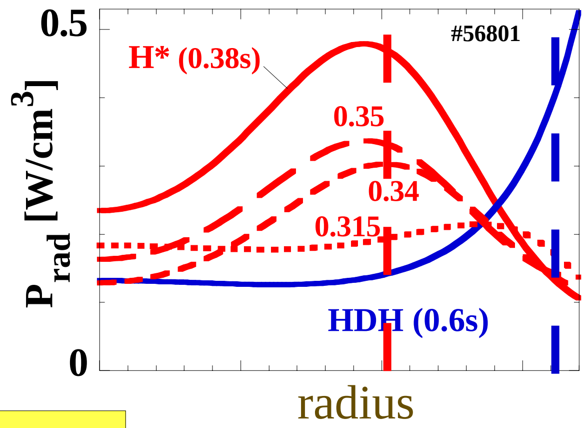


P_{rad} rises rapidly

inside separatrix in H*

and then shifts

to outside in HDH

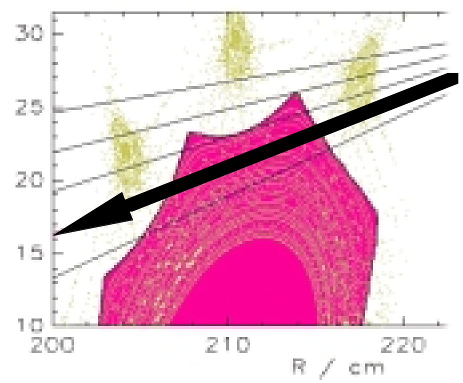


FeXVI radiation rises rapidly in H*

and then is quenched in HDH

Some activity is visible on Hα

BIV setup



E_r, T_e^{ped} & T_i^{edge}

all fall

for H* -> HDH

-> less steep edge profiles?

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H*/HDH

Profile Comparison: H* & HDH

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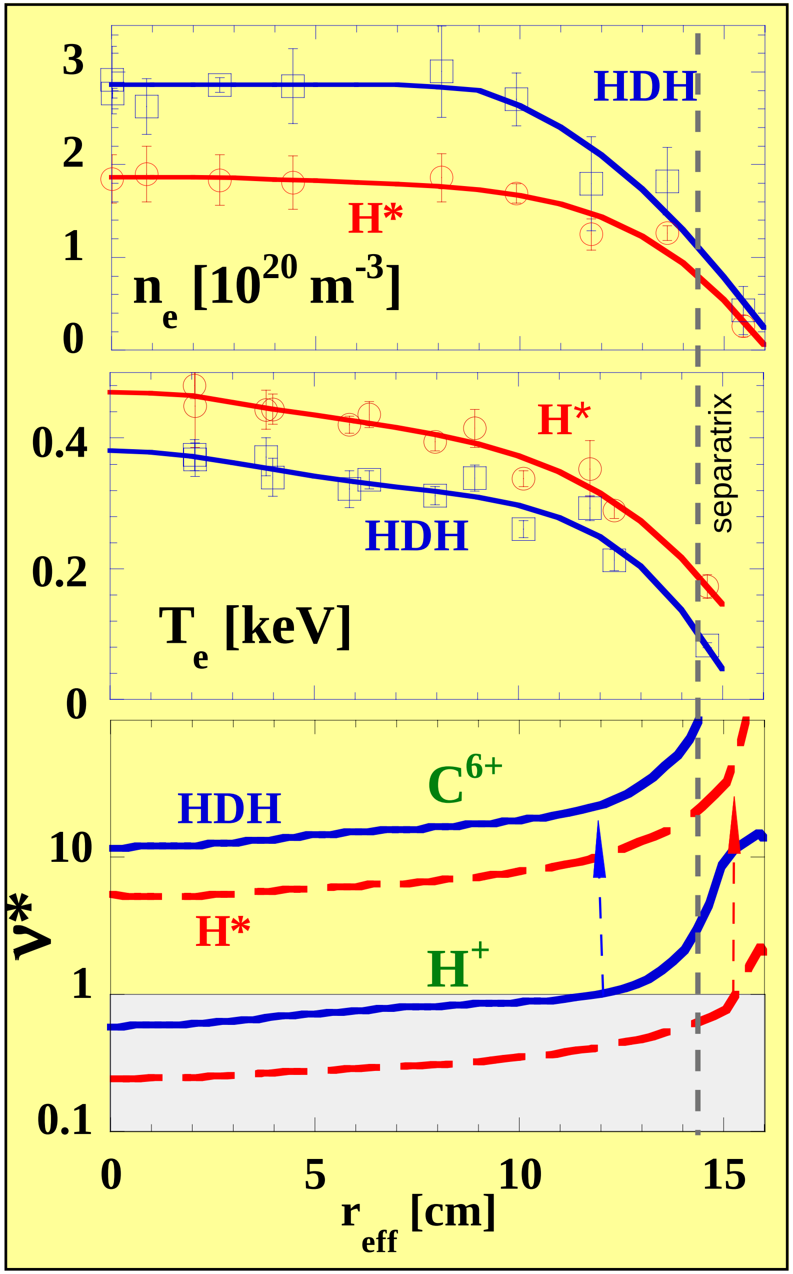


n_e profiles for
H* & HDH
some problems
with Thomson data
=> **edge gradient**
not resolved

T_e profiles for
H* & HDH

ν* for C^{6+} & H^+
C^{6+} collisional
H^+ not collisional
=>
Ti-screening
could be a factor

1

$n_e(r)$ & $T_e(r)$ are similar in form
=>
no major differences expected
as in the case of NC - HDH

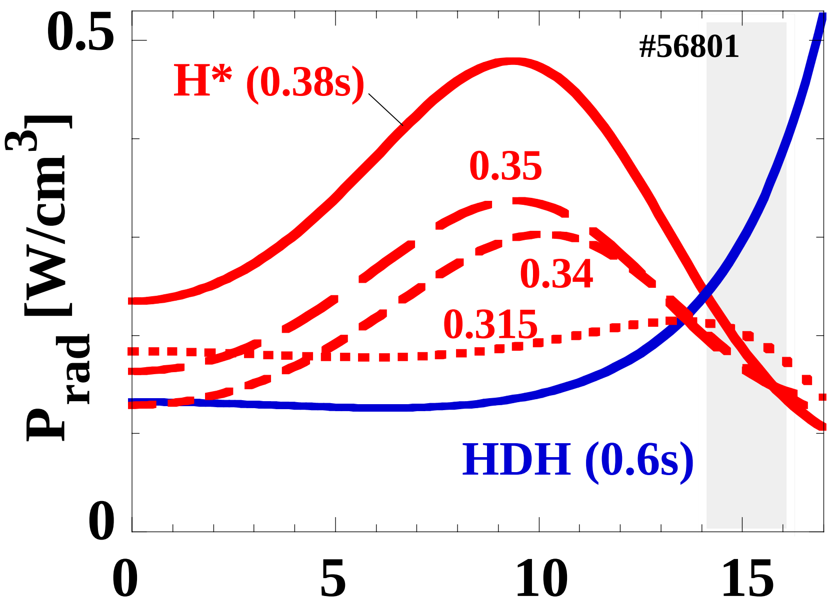
2

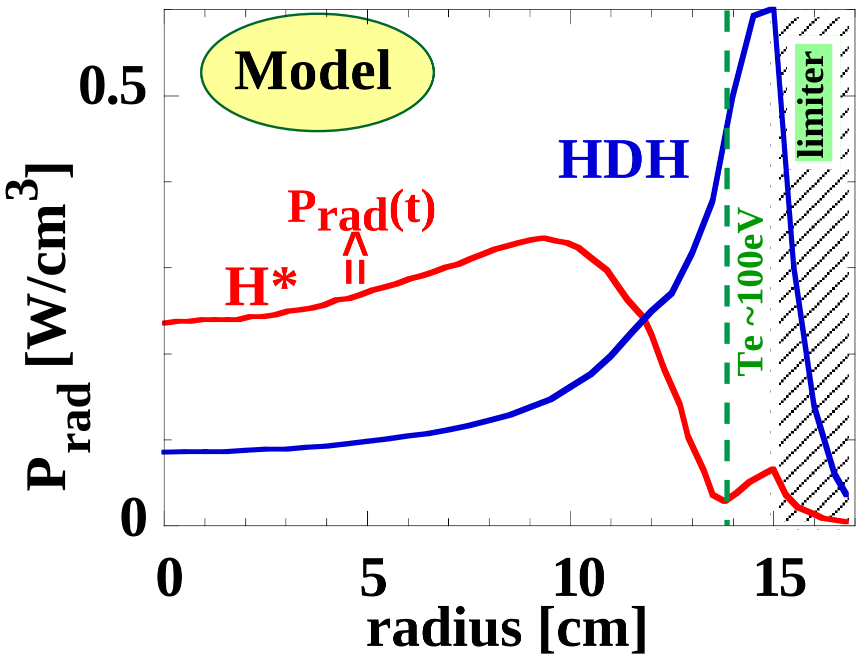
Collisionality more than
factor two higher for HDH
BUT
Ti- Screening conditions
are predicted for H* & HDH

Impurity Behavior of H* Can Be Modeled by Assuming Diffusion is NOT Enhanced at the Edge

H*/HDH

The spatial and temporal behavior of H*can be qualitatively modeled using the same assumptions as for HDH
-> but without an enhanced diffusion in the gradient region <-





Burhenn Thurs. 12:15

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H*/HDH

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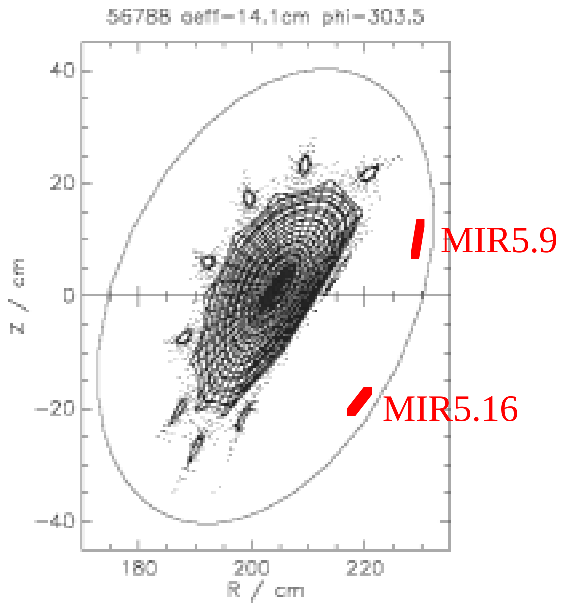
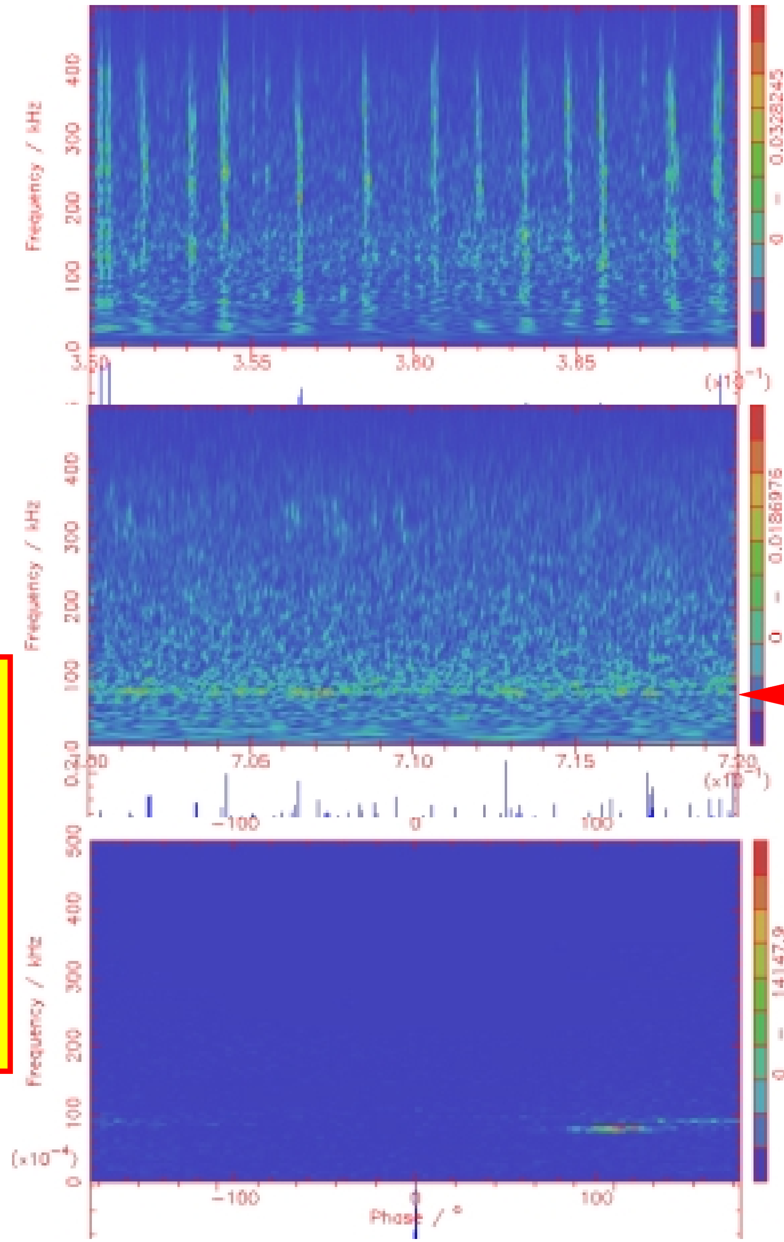
H*-HDH Comparison

Mirnov: Electromagnetic Fluctuations





H*: 0.35-0.37s
ELMs are visible

HDH: 0.7-0.72s
Weak coherent oscillation at ~80kHz

HDH: 0.7-0.72s
phase shift ~ 100 deg. between MIR5.9 & 16

The spectrum is the same for a Mirnov coil mounted on an RCP and brought into the vicinity of the separatrix

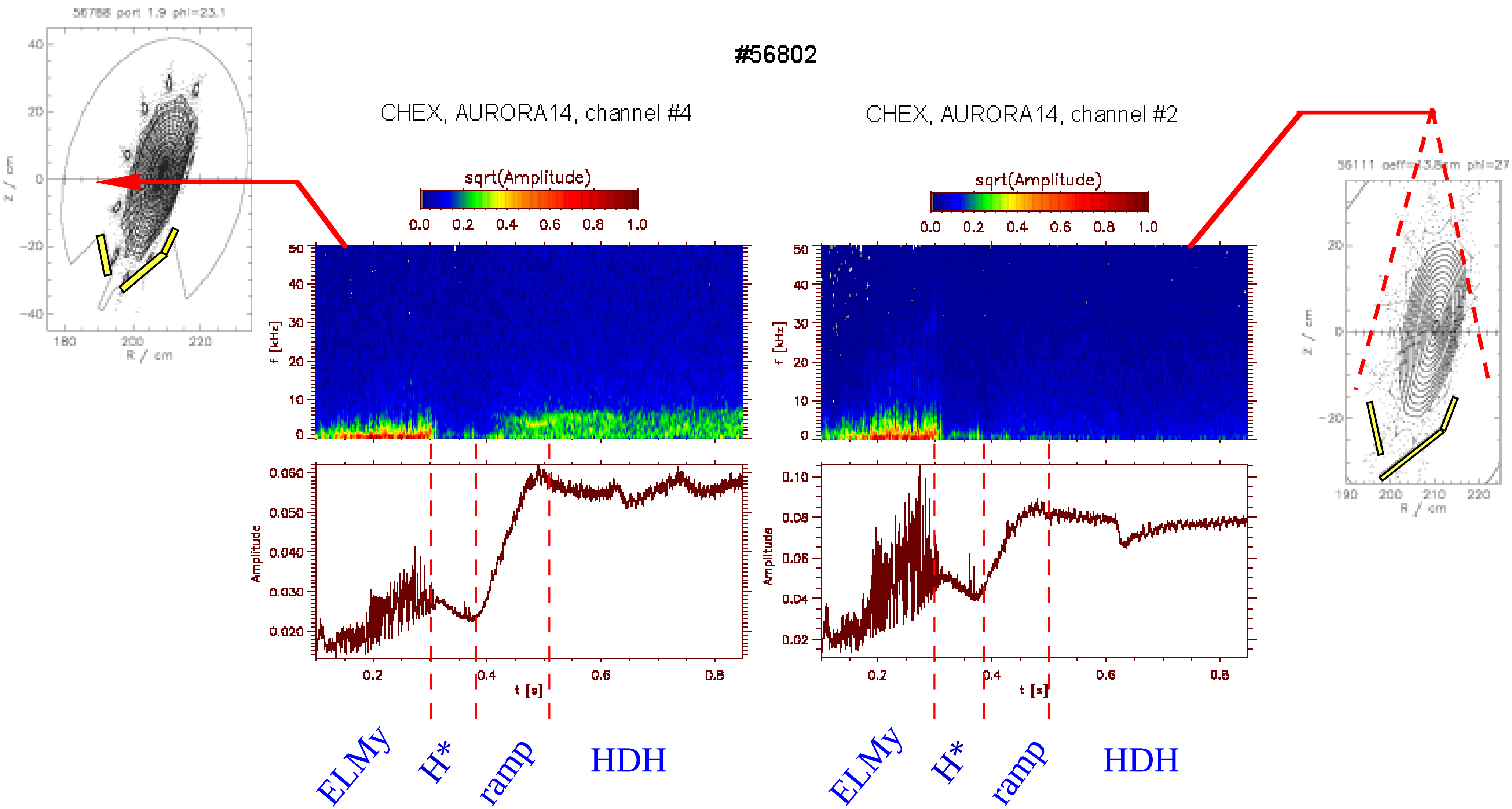
NOT characteristic of QC-mode

bäumel
werner

H*/HDH

H*-HDH Comparison

Global Hα: Horizontal View vs. Divertor



Fluctuations (f<10kHz) in horizontal Hα, but not target plate Hα.

H*/HDH

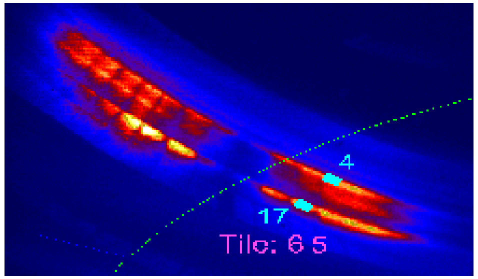
H*-HDH Comparison

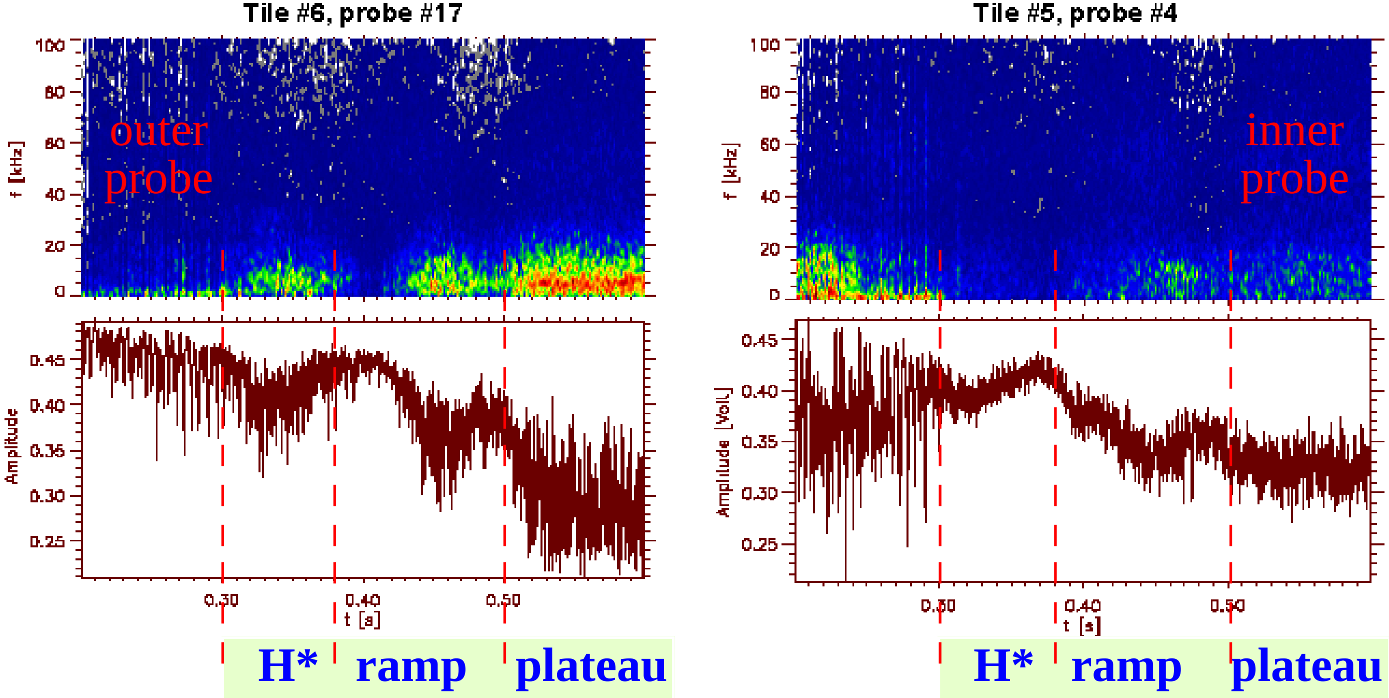
Target Plate Langmuir Probes: Isat Fluctuations

Gadelmeier
Klose

Module 2, upper divertor

#56802
iota_old=0.561, Bz=-12 mT, Icc=0





* I_{sat}(f<10kHz) fluctuations apparent in outer probe during HDH
* No difference in inner probe.

→ **Flux tube localization?**

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SUMMARY

- of basic HDH features -

The Wendelstein 7-AS High Density H-Mode is an ELM-free H-mode

- has broad, flat n_e-profiles with a steep n_e-gradient at edge
- has parabolic-like T_e-profiles
- collisionality: impurities in Pfirsch-Schlüter-, background plasma in plateau-regime

- with low impurity and high energy confinement times
- allows steady-state operation [stationary $n_e(t)$ and $P_{rad}(t)$] for $n_e \leq 4\ 10^{20}/m^3$
- radiates outside the confinement region
  ...up to 90% of the heating power

- exists above a power-dependent density threshold
- exists for detached plasma at target plates and up to density limit
- exists over large Bt range (0.9-2.5T)
- exists up to highest beta attained (3.4%)
- exists for hydrogen and deuterium plasmas, with “interesting differences“
- exists over a variety of magnetic configurations...including limiter-plasmas (high NBI)

HDH is robust
but not understood,

The genesis of HDH is still unclear.

Ti - screening in the Pfirsch-Schlüter regime may be one (minor) factor.

But, there is certainly more... => enhanced edge diffusion?

Some similarities to EDA H-mode of C-Mod (ELM-free, steady-state)

- where a quasi-coherent mode is thought responsible for impurity flushing

but so far no edge-localized transport indicators have been identified:

Mirnov Coils	- spatially swept to near separatrix & at the wall,
RCP	- spatially swept to near separatrix to probe for Isat fluctuations
Reflectometer	- to probe edge density fluctuations in regions at 6, 8,12·10^{19} m^{-3}
Hα	- flux signals at target plate and midplane
probes at TP	- Isat fluctuations at target plate

but data evaluation continues....

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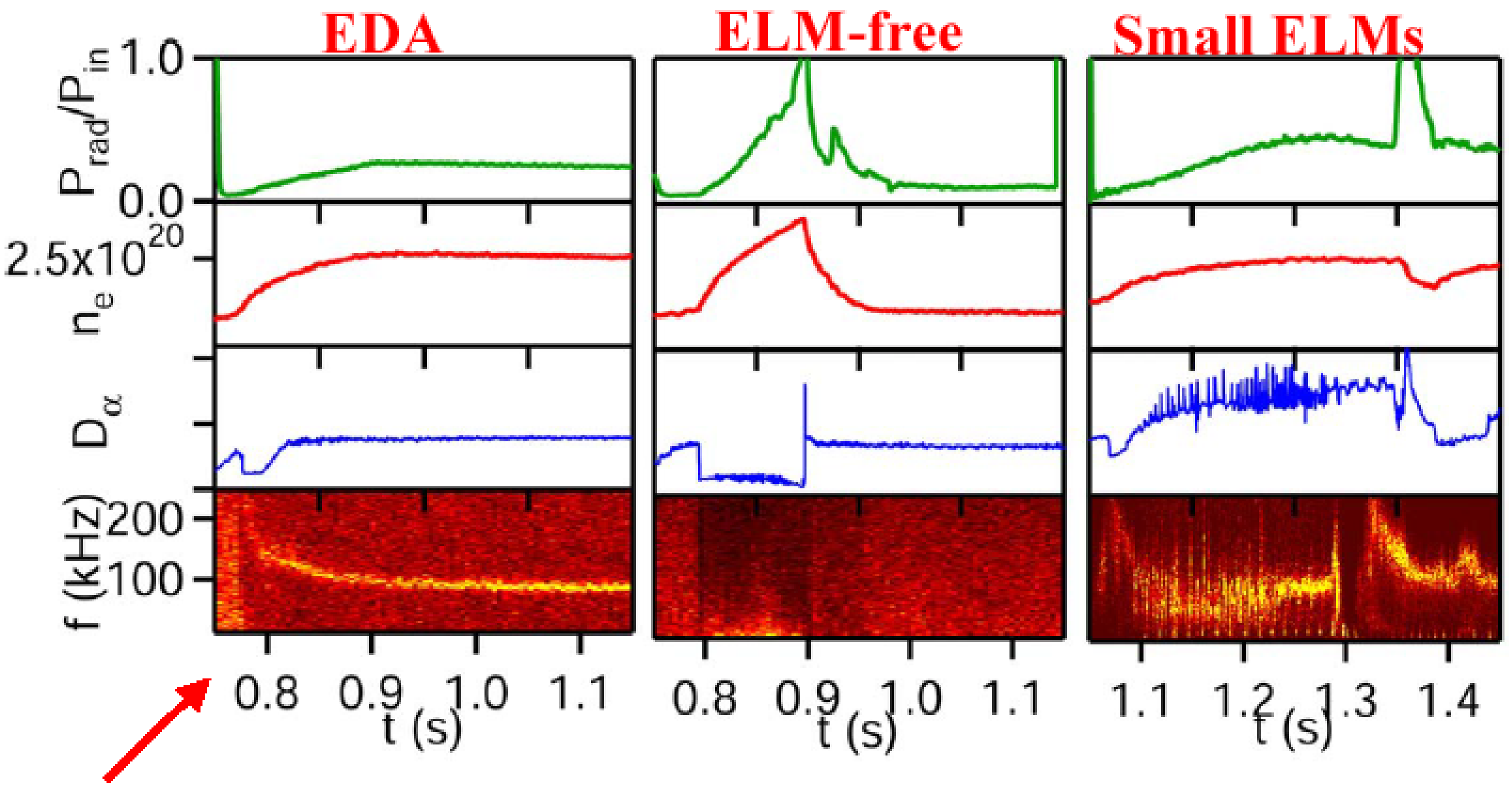
EDA vs. HDH

C-Mod EDA H-Mode

- D.A.Mossessian...44th APS (2002), Orlando -



QC mode associated with steady-state EDA provides for enhanced impurity transport

ELM-free -> no fluctuations => impurity accumulation and radiative collapse

ELMs - increasing ne and Prad suggest transport mechanism different from EDA

Enhanced Dα (EDA) H-mode is ELM-free with no impurity accumulation
- with high confinement -

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EDA vs. HDH

EDA - HDH Comparisons

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	EDA	HDH
understood?	getting close?	no
reactor-relevant	doubtful	LHD/W7X...?
relevant physics?	yes	yes
sensitive to configuration?	yes	not very
capable of detached discharges?	no?	yes
fraction of Greenwald?	0.7	“2“
standard mode of operation	no	yes

ROBUST: HDH does not require extensive wall conditioning

Boronization necessary at start
- but one “coating“ is adequate for months of operation.

Ten minutes He GDC at beginning of day
- is sufficient for an entire day of HDH discharges.

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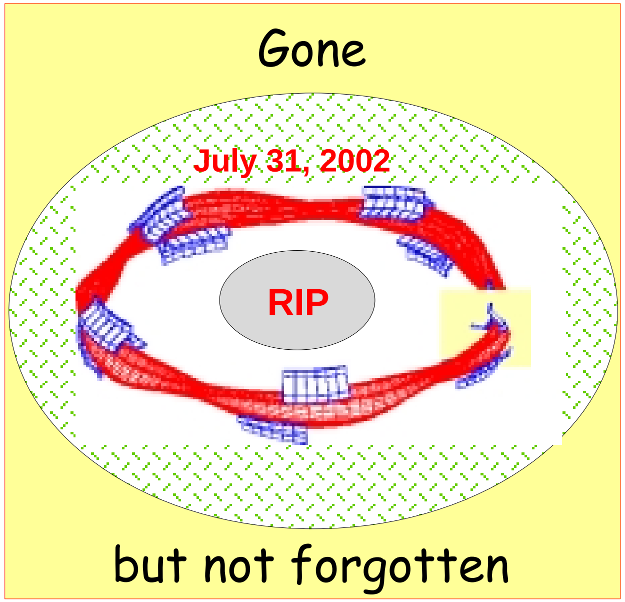
Where Do We Go from Here?

HDH - a Mode of the Past, or One for the Future?



1. W7-AS is now deactivated, but lots of data, remains to be evaluated.

2. Cooperation with LHD, now that higher power levels have been attained? Or, Heliotron J?

3. Studies of
   - ELM-free H-modes
   - ELMs

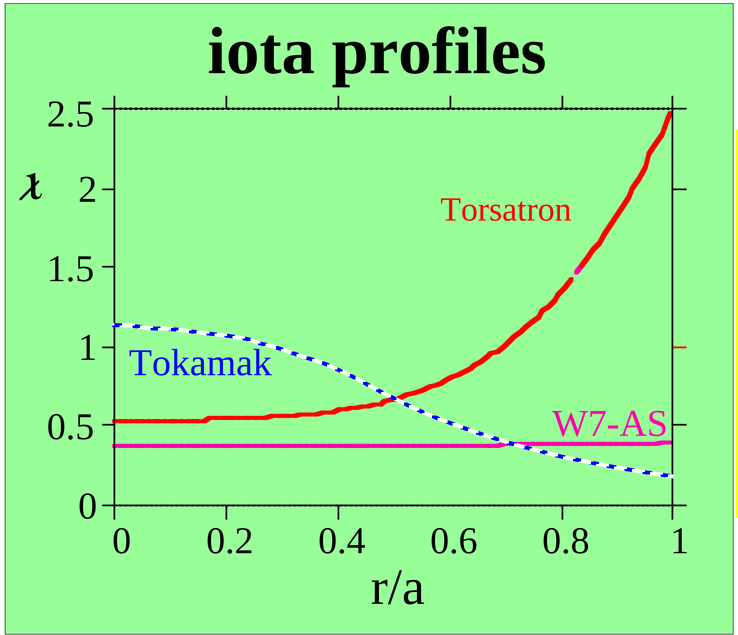
   to compliment tokamak experience

no shear
no net current
radically different x-point structure

Where Do We Go from Here?

-a beginning? -

K. McCormick is the stellarator representative to the ITPA task group: SOL/Divertor Physics



Different current, shear and magnetic field configurations will allow illumination of aspects of ITER-relevant physics...

- ELM-free H-modes
- or ELM studies

Complementary Workshop Contributions

W7-AS Summary

R. Jaenicke...“Summary of W7-AS Results After 14 Years...“, Monday 09:00

W7-AS High Density Operation

S. Bäumel...“Investigation of Fluctuations in H*-HDH Regimes...“, P.Mo12

W7-AS Divertor Experiments

R. König...“Divertors for Helical Devices...“, Tuesday 10:15

W7-AS Divertor Experiments

P. Grigull...“Behavior of the W7-AS Island Divertor“, Thursday 11:15

W7-AS Impurity Transport:

R. Burhenn ...“Impurity Transport in the W7-AS Stellarator“, Thursday 12:15

W7-AS 3D Edge Transport Calculations with EMC3

Y. Feng...“Physics and Modelling of the W7-AS Island Divertor“, Friday 10:15

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Stellarator REFERENCES
- a selection -

W7-AS

Beta-Limit: A.Weller... IAEA-CN-94/EX/S3-1, Lyon 2002
A.Weller... 30th EPS, St.Petersburg 2003

HDH-Mode: P.Grigull...Plasma Phys. Control. Fusion **43** (2001) A175
K.McCormick...Phys. Rev.Letters **89** (2002) 015001
K.McCormick...J.Nucl.Mater. **313-316** (2002) 1131

Impurity Transport:
R. Burhenn... EPS, St. Petersburg 2003
K. Ida...accepted for publishing in PPCF

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Tokamak EDA H-Mode REFERENCES

- a selection -

C-MOD EDA H-Mode

M.Greenwald...Plasma Phys. Control. Fusion 42 (2000) A263

J.A.Snipes...Plasma Phys. Control Fusion 43 (2001) L23

A.E.Hubbard...Physics of Plasmas 8 (2001) 2033

D.A.Mossessian...Plasma Phys. Control. Fusion 44 (2002) 423

A.Mazurenko...Phys. Rev. Letters 89 (2002) 225004

DIII-D EDA H-Mode

D.A.Mossessian, R.J.Groebner...Physics of Plasmas 10 (2003) 689

ASDEX-Up EDA H-Mode Attempt

W.Suttrop...A.Hubbard IAEA-CN-94/EX/P5-07, Lyon 2002

JET EDA H-Mode (the beginning)

G.Maddison...Plasma Phys. Control. Fusion 44 (2002) 1937

JFT-2M HRS H-Mode

K.Kamiya... IAEA-CN-94/EX/P2-05, Lyon 2002

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Tokamak Quiescent H-Mode REFERENCES
- a selection -

DIII-D QH-Mode

K.H. Burrell...Plasma Phys. Control. Fusion **44** (2002) A253

P.H. West...30th EPS, St. Petersburg, "Quiescent H-Mode...DIII-D..."

ASDEX-Up QH-Mode

W. Suttrop...Plasma Phys. Control. Fusion **45** (2003) 1399

http://www.iop.org/EJ/abstract/0741-3335/45/8/302

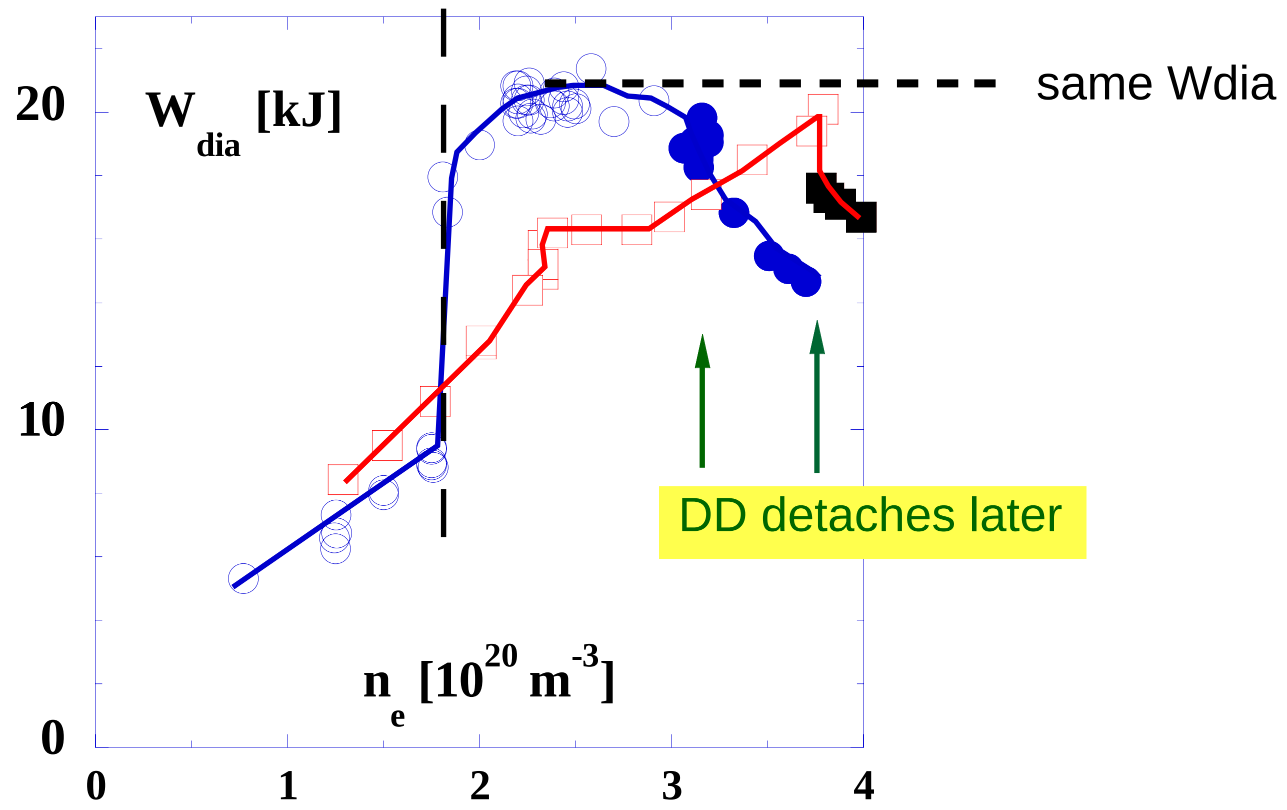
W. Suttrop...30th EPS, St. Petersburg, "ELM-free Stationary H-Modes..."

http://eps2003.ioffe.ru/PDFS/P1_125.PDF

Isotope Effect: W_{dia} vs. n_e for: $H^o \rightarrow H^+$ & $D^o \rightarrow D^+$

sharp transition for HH

for DD, Wdia increases ~ linearly with density



P_{nbi}^{abs} ~ 1.4MW

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Isotope Effect: Profile Comparison for n_e-scan: 2MW NBI: H^o -> H^+ vs. D^o -> D^+

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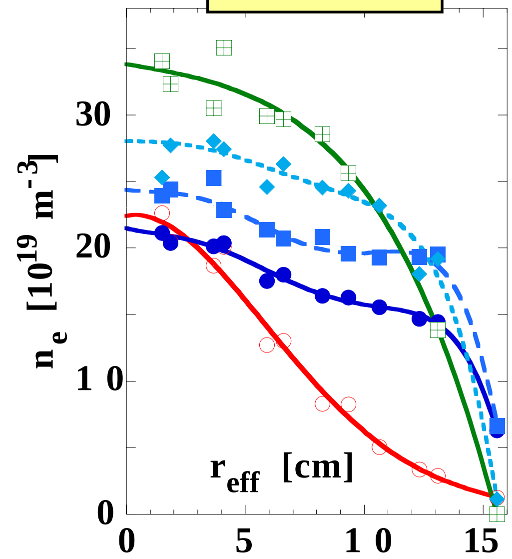
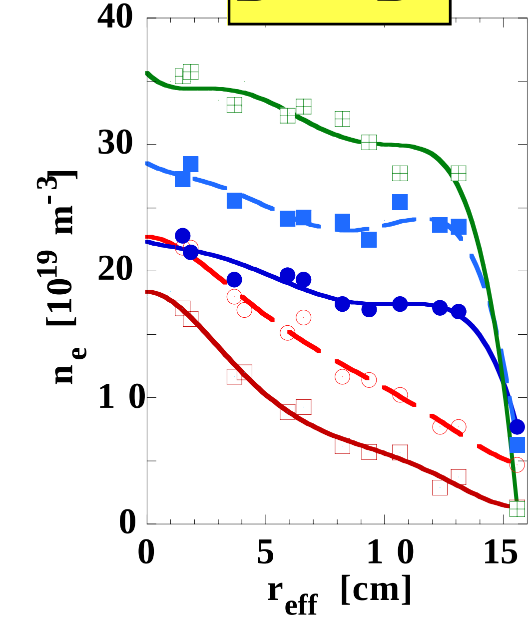
H^o -> H^+

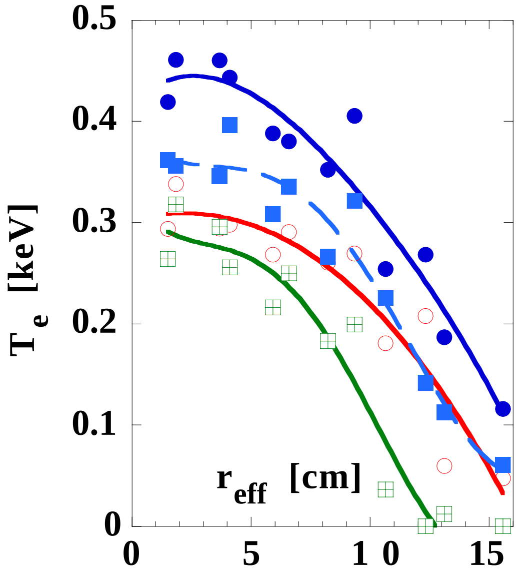


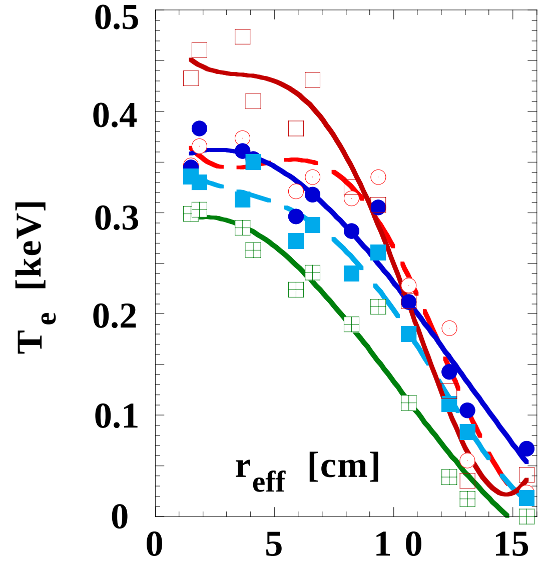
D^o -> D^+



D-D maintains flatter profiles into detachment

for D-D the profile form change from NC to HDH is not so large





for D-D, higher T_e at edge in detachment

for D-D NO increase in T_e from NC to HDH