Overview of ASDEX Upgrade Results

Otto Gruber for the ASDEX Upgrade Team

Presented at the 21st IAEA Conference
at Chengdu (China), 16 – 21 Oct 2006

ASDEX Upgrade Team:

C. Angioni1, C.V. Atanasiu2, M. Balden1, G. Becker1, W. Becker1, K. Behler1, K. Behringer1, A. Bergmann1, T. Bertoncelli1, R. Bilato1, V. Bobkov1, T. Bolzonella3, A. Bottino1, M. Brambilla1, F. Braun1, A. Buhler1, A. Chankin1, G. Conway1, D.P. Coster1, T. Dannert1, S. Dietrich1, K. Dimova1, R. Drube1, R. Dux1, T. Eich1, K. Engelhardt1, H.-U. Fahrbach1, U. Fantz1, L. Fattorini4, R. Fischer1, A. Flaws1, M. Foley5, C. Forest6, P. Franzen1, J.C. Fuchs1, K. Gál7, G. Gantenbein8, M. García Muñoz1, L. Giannone1, S. Gori1, S. da Graça1, H. Greuner1, O. Gruber1, S. Günter1, G. Haas1, J. Harhausen1, B. Heinemann1, A. Herrmann1, J. Hobirk1, D. Holtum1, L. Horton1, M. Huart1, V. Igochine1, A. Jacchia9, F. Jenko1, A. Kallenbach1, S. Kálvin7, O. Kardaun1, M. Kaufmann1, M. Kick1, G. Koscis7, H. Kollotzek1, C. Konz1, K. Krieger1, H. Kroiss1, T. Kubach8, T. Kurki-Suonio10, B. Kurzan1, K. Lackner1, P.T. Lang1, P. Lauber1, M. Laux1, F. Leuterer1, J. Likonen11, A. Lohs1, • Lyssoivan12, C. Maggi1, H. Maier1, K. Mank1, A. Manini1, M.-E. Manso4, P. Mantica9, M. Maraschek1, P. Martin3, M. Mayer1, P. McCarthy5, H. Meister1, F. Meo13, P. Merkel1, R. Merkel1, V. Mertens1, F. Merz1, H. Meyer14, F. Monaco1, H.-W. Müller1, M. Münich1, H. Murmann1, Y.-S. Na1, G. Neu1, R. Neu1, J. Neuhauser1, J.-M. Noterdaeme1, M. Pacco-Düchs1, G. Pautasso1, A.G. Peeters1, G. Pereverzev1, S. Pinches1, E. Poli1, M. Püschel1, T. Pütterich1, R. Pugno1, E. Quigley5, I. Radivojevic1, G. Raupp1, M. Reich1, T. Ribeiro4, R. Riedl1, V. Rohde1, J. Roth1, M. Rott1, F. Ryter1, W. Sandmann1, J. Santos4, K. Sassenberg5, G. Schall1, H.-B. Schilling1 J. Schirmer1, A. Schmid1, W. Schneider1, G. Schramm1, W. Schustereder15, J. Schweinzer1, S. Schweizer1, B. Scott1, U. Seidel1, M. Serbu1, F. Serra4, Y. Shi16, A. Silva4, A.C.C. Sips1, E. Speth1, A. Stäbler1, K.-H. Steuer J. Stober1, B. Streibl1, D. Strintzi1, E. Strumberger1, W. Suttrop1, G. Tardini1, C. Tichmann1, W. Treutterer1, C. Tröster1, M. Tsalas17, L. Urso1, E. Vainonen-Ahlgren11, P. Varela4, L. Vermare1, D. Wagner1, M. Wischmeier1 E. Wolfrum1, E. Würsching1, Q. Yu1, D. Zasche1, T. Zehetbauer1, M. Zilker1, H. Zohm1.

Contributing Institutes

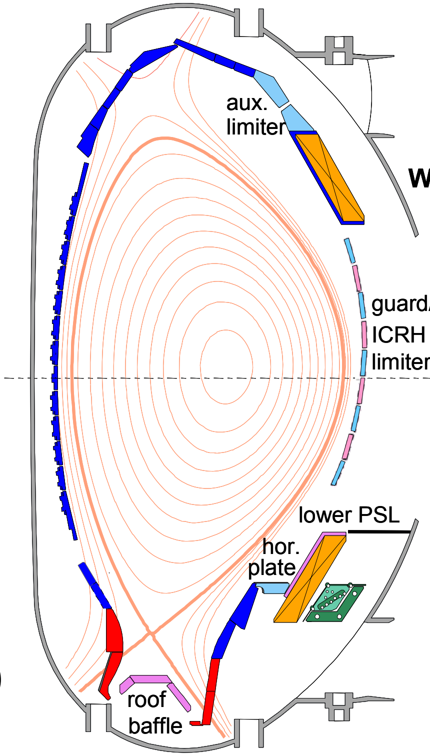
1 Max-Planck-Institut für Plasmaphysik, EURATOM Association-IPP, Garching, Germany
2 Institute of Atomic Physics, EURATOM Association-MEdC, Romania,
3 Consorzio RFX, EURATOM Association-ENEA, Padova, Italy,
4 CFN, EURATOM Association-IST Lisbon, Portugal,
5 Physics Dep., University College Cork, Association EURATOM-DCU, Ireland,
6 University of Wisconsin, Madison, USA.
7 KFKI, EURATOM Association-HAS, Budapest, Hungary,
8 Institut für Plasmaforschung, Stuttgart University, Germany,
9 IFP Milano, EURATOM Association-ENEA, Italy,
10 HUT, EURATOM Association-Tekes, Helsinki, Finland,
11 VTT, EURATOM Association-Tekes, Espoo, Finland,
12 LPP-ERM/KMS, EURATOM Association-Belgian State, Brussels, Belgium,
13 NL Risø, EURATOM Association-RISØ, Roskilde, Denmark,
14 UKAEA Culham, EURATOM Association-UKAEA, United Kingdom,
15 University of Innsbruck, EURATOM Association-ÖAW, Austria
16 IPP, CAS, Hefei, China,
17 NCSR Demokritos, EURATOM Association-HELLAS, Athens, Greece

AUG programme to prepare / in parallel to ITER

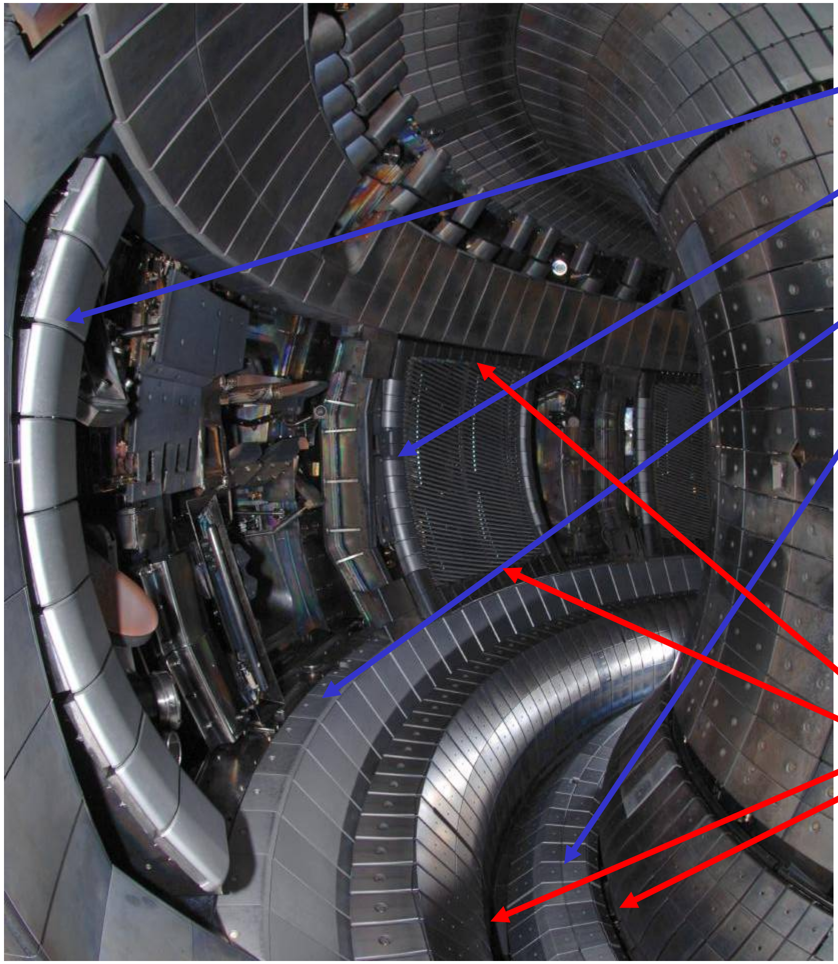
- **Main aim is to establish the physics base for ITER (and DEMO):**
  - consolidation of the 'standard' H-mode scenario
  - exploration of ‚advanced' modes beyond the standard scenario
- **Understanding of physics elements**
  - **transport**
  - **fast particles and NBCD**
  - **H-mode edge and ELM tailoring**
  - **disruption mitigation**
  - **MHD control with ECCD**
  - **tungsten wall and divertor operation**
- **Integration into improved scenario beyond reference**
  - **Improved H-mode (ITER Hybrid scenario)**
  - ITER relevant digital CODAC system
- Direct influence on ITER component design:
  PFC material, heating/CD systems, ECRF system
- Strategy: in close collaboration within EU fusion programme, ITPA TGs

AUG enhancements 2004-2006:

- towards a tungsten first wall: 36 m^2 or 85% of PFC area)
  2005: - all LFS limiters (water cooled)
  - roof baffle with thin W coating (<4 μm)
  2006: lower divertor target plates (200 μm W)
- 4 steerable ECRH mirrors installed
- first two-frequency gyrotron: leak after commissioning (≤1 MW / 10 s / 105 & 140 GHz)
- pellet injection systems
  - centrifuge (HFS launch capability, variable pellet size,< 1200 m/s)
  - blower gun (optimized for decoupling ELM pacing and refuelling)
- new CODAC commissioned
  - reduced cycle time <1.5ms
  - extended regime recognition & performance control
  - real-time diagnostics →replaces CAMACs



AUG enhancements: **Towards a full W machine 2005**



- in 2005 **"thin"** W coating of
  - 4 guard limiters at LFS (water cooled)
  - 8 ICRH antenna side limiters
  - top of bottom PSL
  - roof baffle

- in 2006
  - upper and lower ICRH limiters
  - W coated bottom target tiles (200 μm)

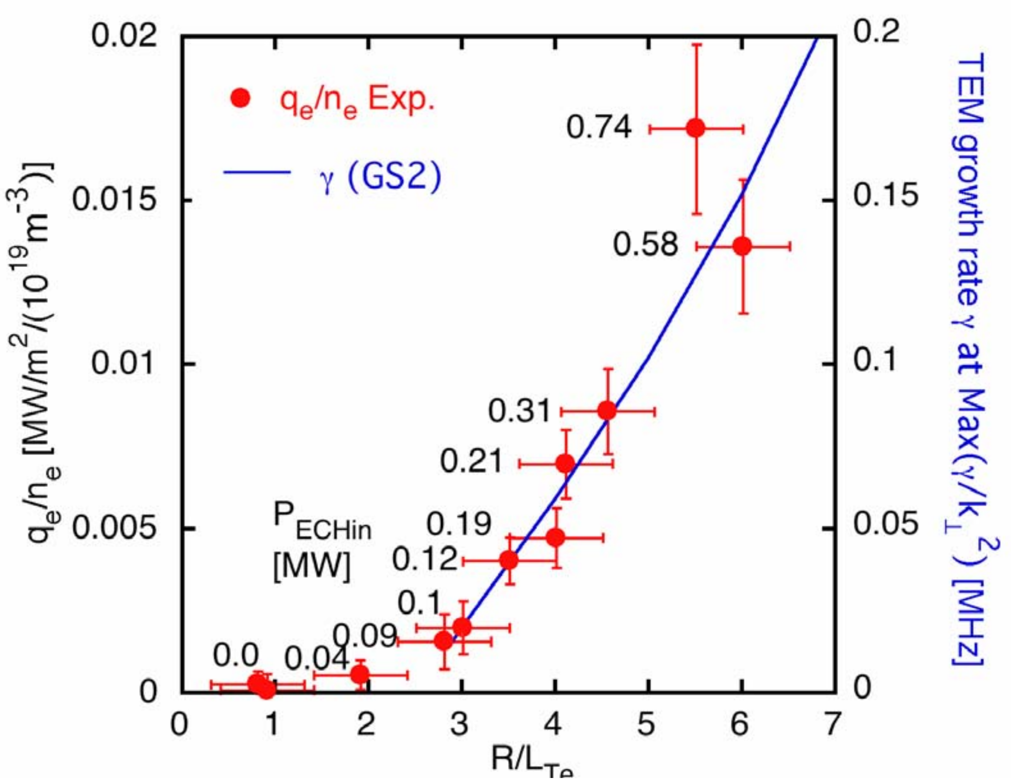
→full tungsten machine

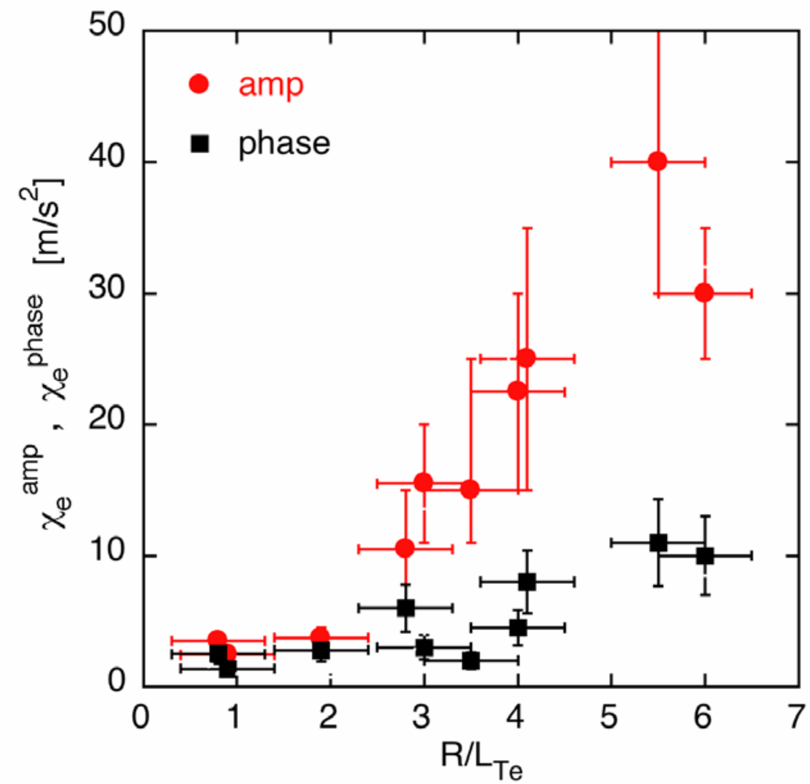
ITER start-up configuration ?

Understanding of anomalous transport → predictions

- response of different transport channels on heat and momentum input
- comparison with gyrokinetic simulations
→ TEM and ITG turbulence dominate in different parameter regimes

Pure electron heating: **threshold for TEM at R/L_{Te}≈3** Angioni EX/8-5Rb

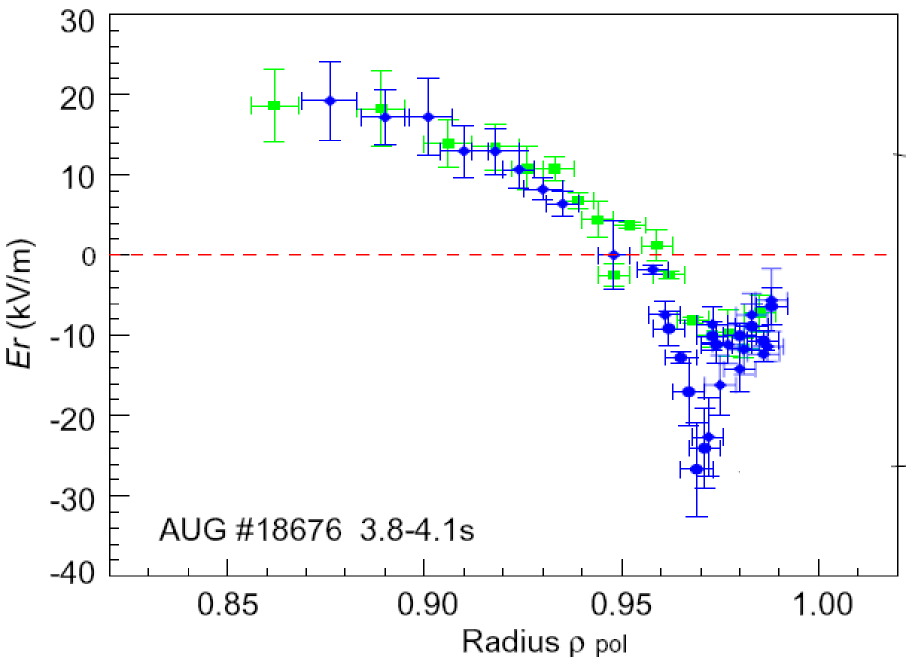


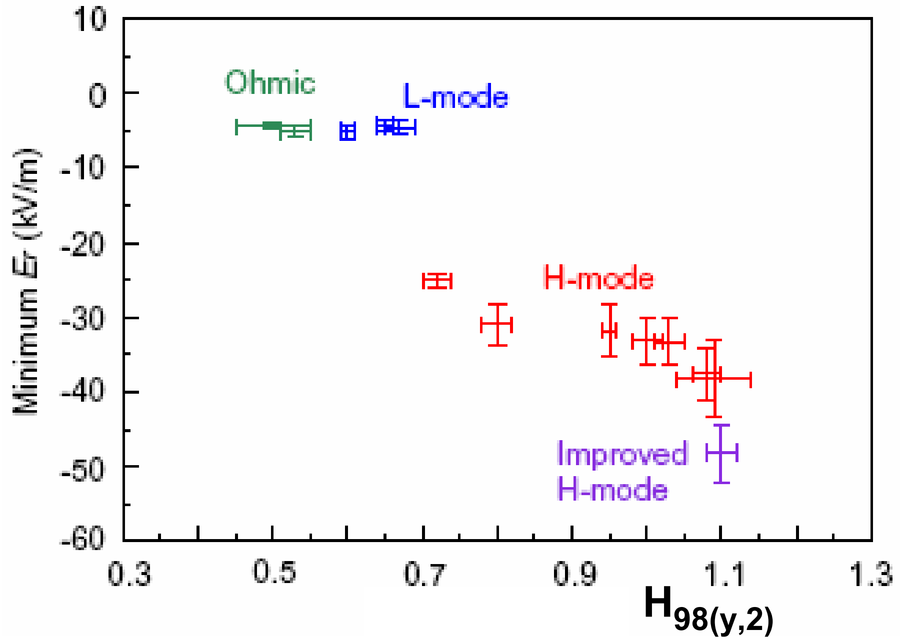


• power balance and heat pulse propagation show a transition through threshold

Transport: **E_r transitions at plasma edge**

- **negative E_r well increases with confinement improvement**
  - coincides with H-mode barrier gradient
  - Doppler reflectometry

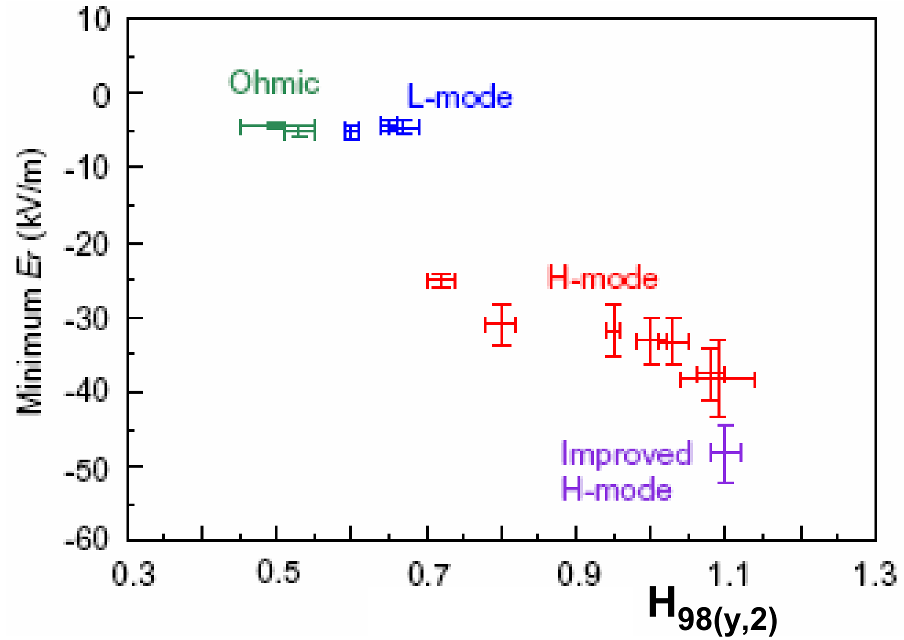




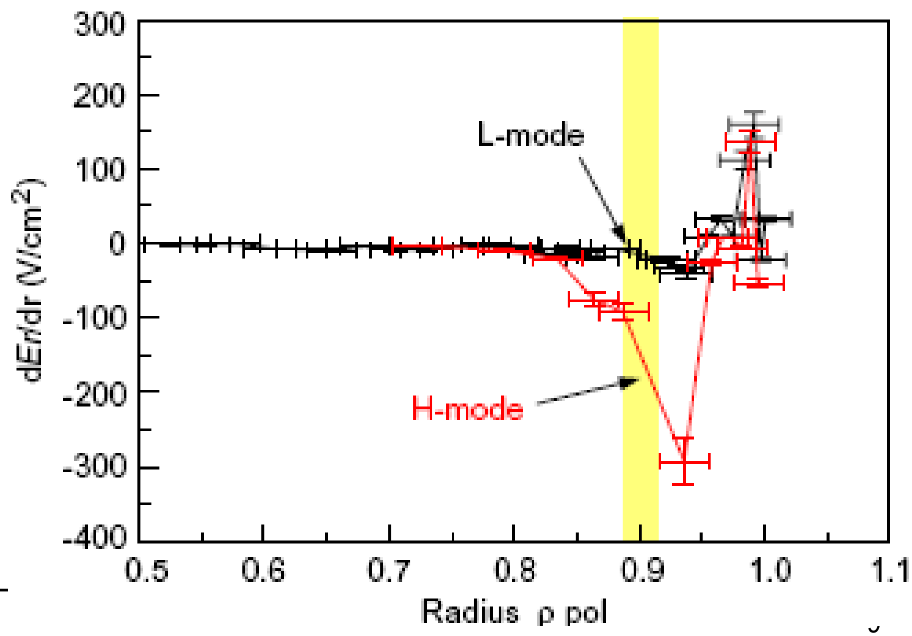
Conway EX/2-1

Transport: E_r transitions at plasma edge

- **negative E_r well increases with confinement improvement**
  - coincides with H-mode barrier gradient
  - Doppler reflectometry



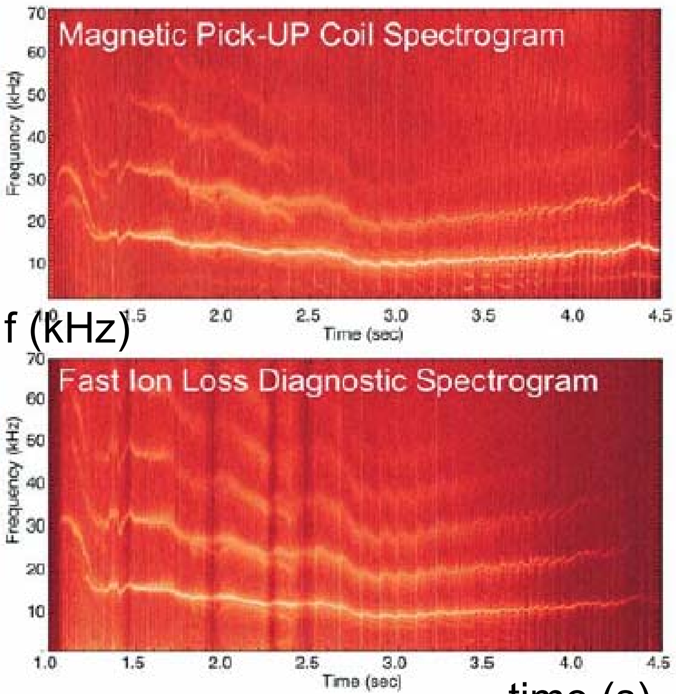
- **E_r shear enhanced as well**
  - 2 channel Doppler at fixed Δf ~ 2GHz
  - negative shear at pedestal increases with confinement
  - shear width ≤5cm



Conway EX/2-1

Fast particle interactions with large scale instabilities

- New: Fast Ion Loss Detector (FILD) with bandwidth of 1 MHz
- **frequency / phase correlations of fast ions with TAEs** (ICRH, ICRH beatwave
- **fast particle losses correlated with low frequency MHD activity:** NTMs, double tearing modes, ELMs



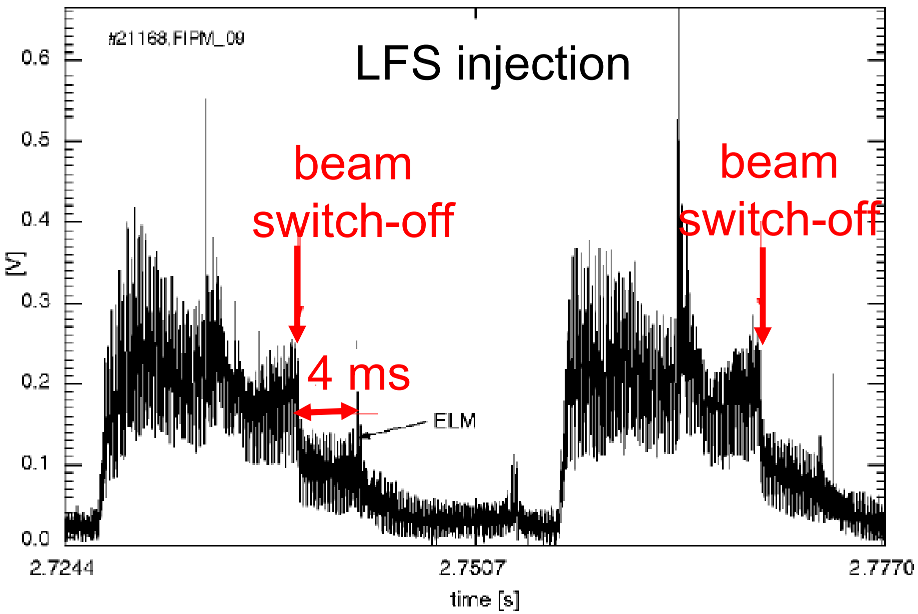
Fast ion losses track the details of the mode

- slow MHD activity like NTM (+harmonics) induces fast particle losses
- FILD signal is modulated with rotating mode in fixed phase relation
- modulated NBI sources with different injection geometry → origin of fast particles
- time scale of losses >100 toroidal orbit transits due to stochasticity of overlapping drift islands caused by the NTM
- NTM stabilization → decrease of losses

Günter EX/6-1

Fast particle interactions with large scale instabilities

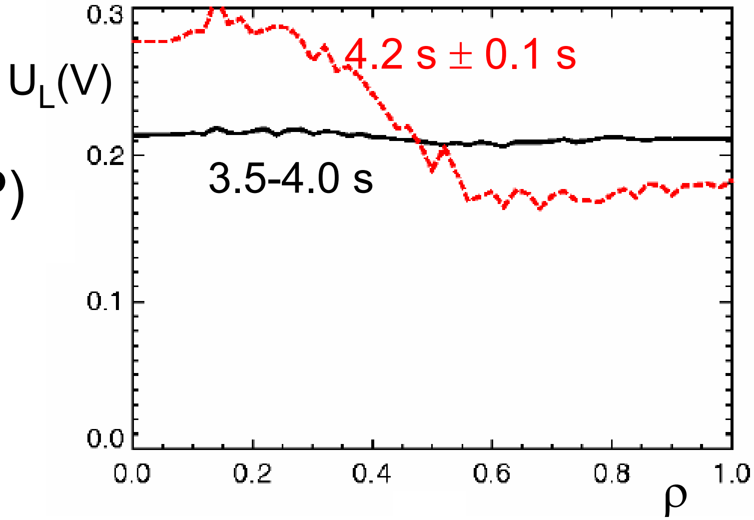
- New: Fast Ion Loss Detector (FILD) with bandwidth of 1 MHz
- **frequency / phase correlations of fast ions with TAEs** (ICRH, ICRH beatwave
- **fast particle losses correlated with low frequency MHD activity:**
- NTMs, double tearing modes, ELMs



- FILD signal caused by DTM
- response time depends on origin
- orbit drifts and slowing down determine delay

Unexpected broadening of NBI driven currents

- beyond a certain heating power, measured and predicted distributions of NBI driven currents deviate (MSE, TRANSP)
- electric field changes cannot be explained by current diffusion

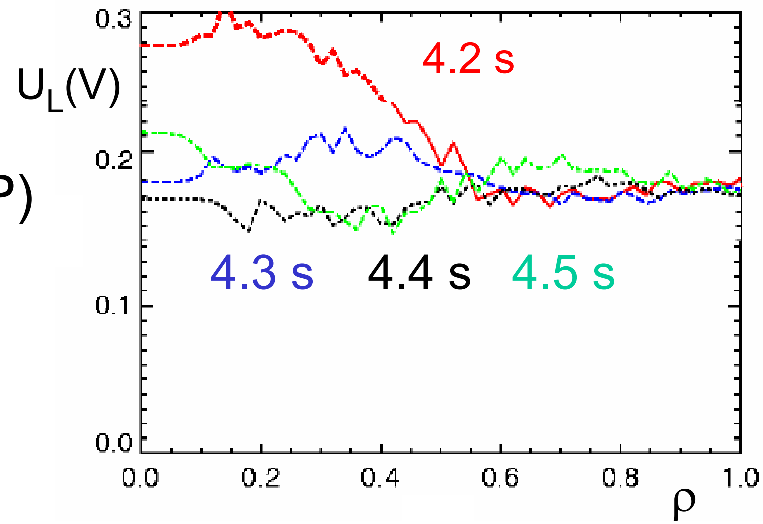


Switch on / off-axis at 4.1 s

Günter EX/6-1, McCarthy TH/P3-7

Unexpected broadening of NBI driven currents

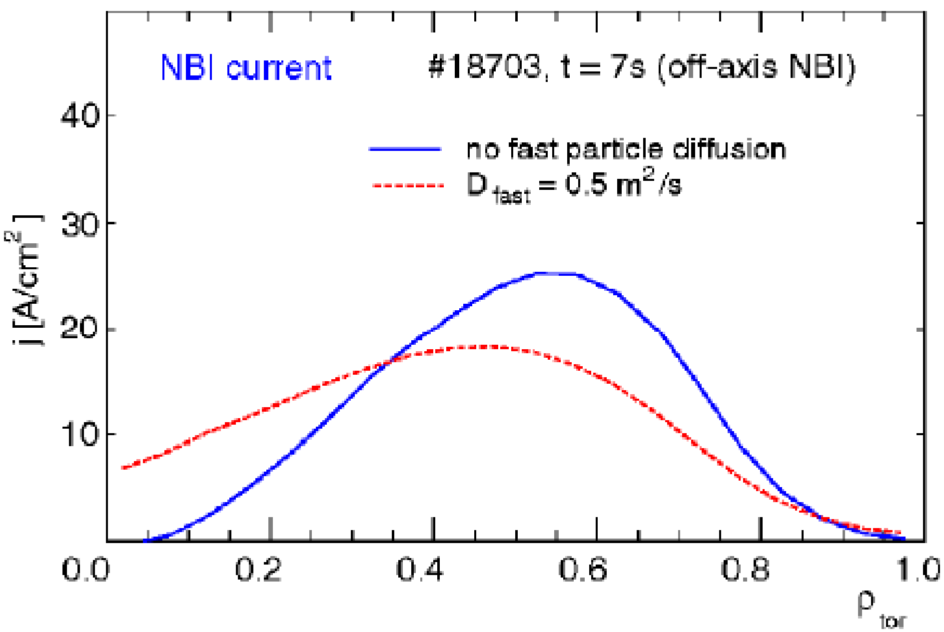
- beyond a certain heating power, measured and predicted distributions of NBI driven currents deviate (MSE, TRANSP)
- electric field changes cannot be explained by current diffusion



Switch on / off-axis at 4.1 s

- **energetic particle diffusion driven by small-scale turbulence** (gyrokinetic code)

→ redistribution of injected ions with $D_{fast} \approx 0.5\ m^2/s$



Günter EX/6-1

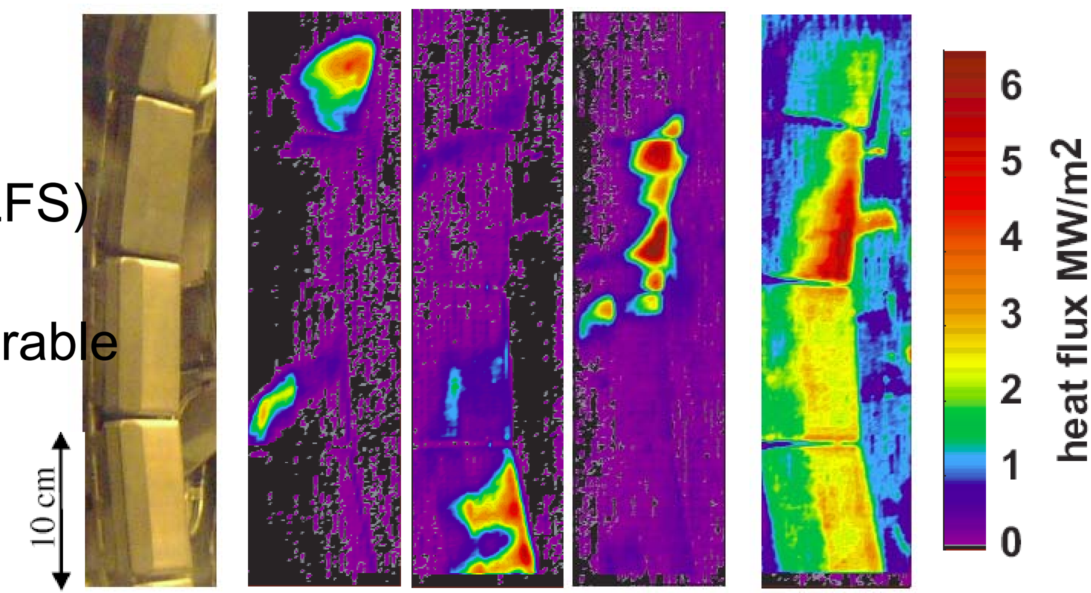
ELMs and disruptions

- most of the ELM and disruption energy is deposited in the divertor
- a smaller fraction goes to the main chamber wall

ITER: small ELM regimes / ELM pacemaking & disruption mitigation mandatory

ELMs:

- helical field aligned structures with a 3-6 cm spatial width and 3-6 km/s rotation velocity
- move radially far into the SOL (LFS)
- heat flux decay length 2-3 cm
- particle flux decay length comparable
- consistent with convective loss along field lines



Neuhauser EX/P8-2

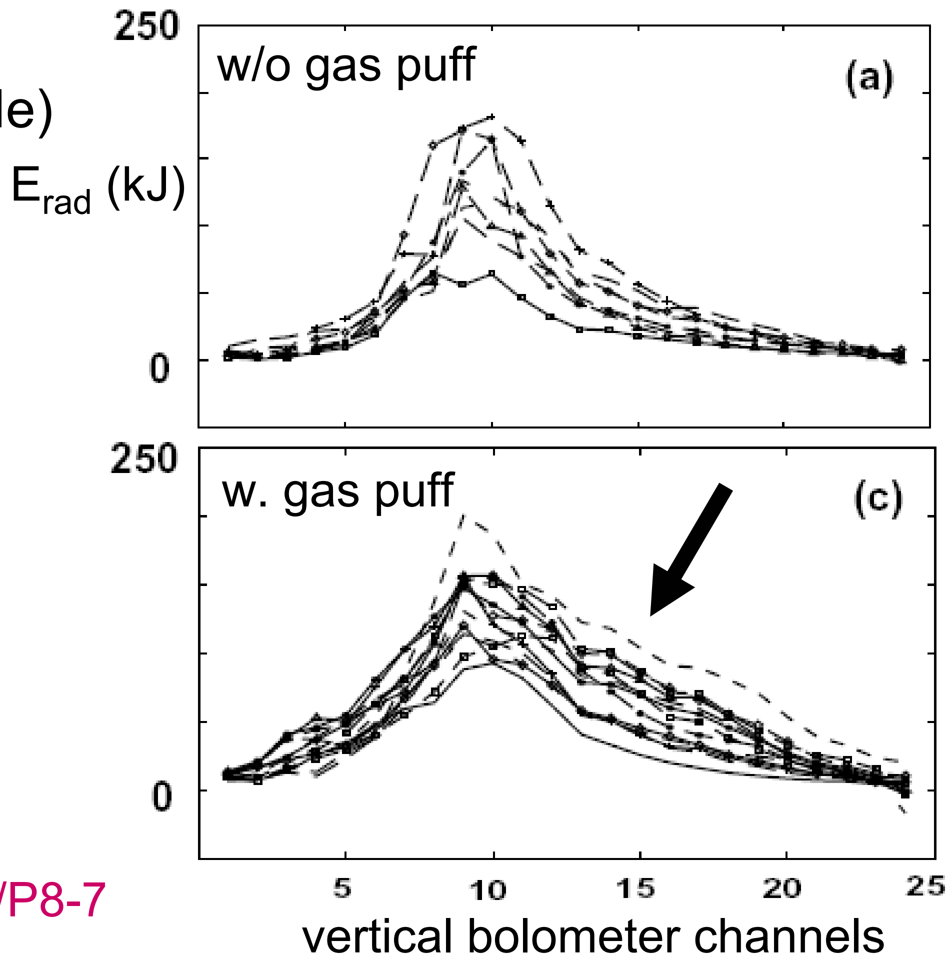
ELMs and disruptions

- most of the ELM and disruption energy is deposited in the divertor
- a smaller fraction goes to the main chamber wall

ITER: small ELM regimes / ELM pacemaking & disruption mitigation mandatory

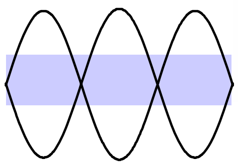
Disruptions:

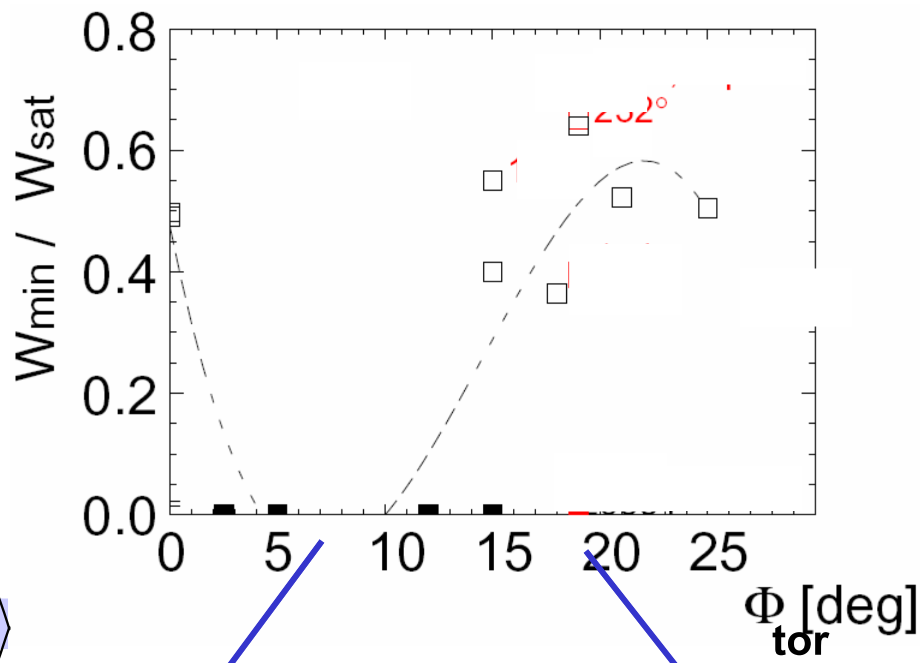
- mitigation by puffing of noble gases (Ne) regularly used at AUG
- significant reduction of force loads on all structures
- divertor heat load mainly reduced by broader radiation and heat deposition profiles in divertor
- further optimization needed: higher gas pressure and amount

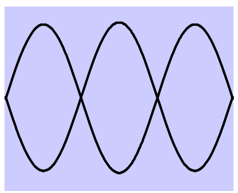


Pautasso EX/P8-7

NTM stabilization: **Influence of ECCD deposition width d**





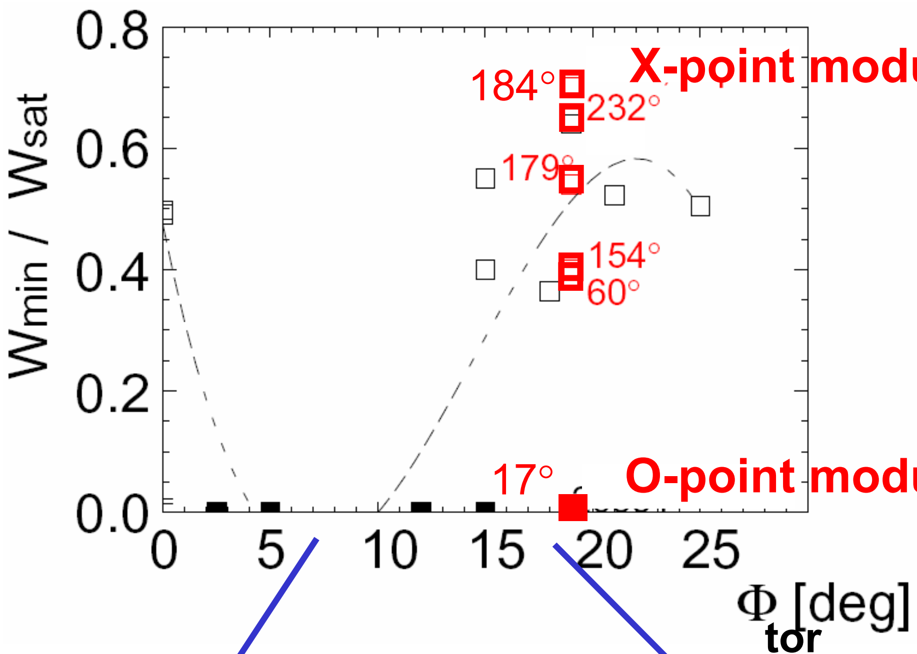


- **narrow deposition W>2d:**
  - I_{ECCD} counts for helical CD
  - full stabilisation with dc ECCD of (3,2) and (2,1) NTMs
  - no advantage of phased ECCD

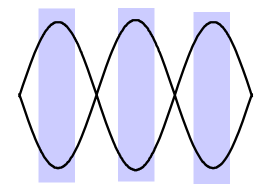
- **broad deposition W<2d:**
  - mimics ITER $W_{marg} \sim \rho_{pol}$
  - I_{ECCD}/d^2 counts for dc ECCD
  - only partial dc stabilization
  - required current increases significantly

$\Rightarrow$ modulated ECCD required (at mode frequency / O-point injection)

NTM stabilization: **Modulated ECCD with broad deposition**



Zohm EX/4-1Rb
Yu TH/P3-13



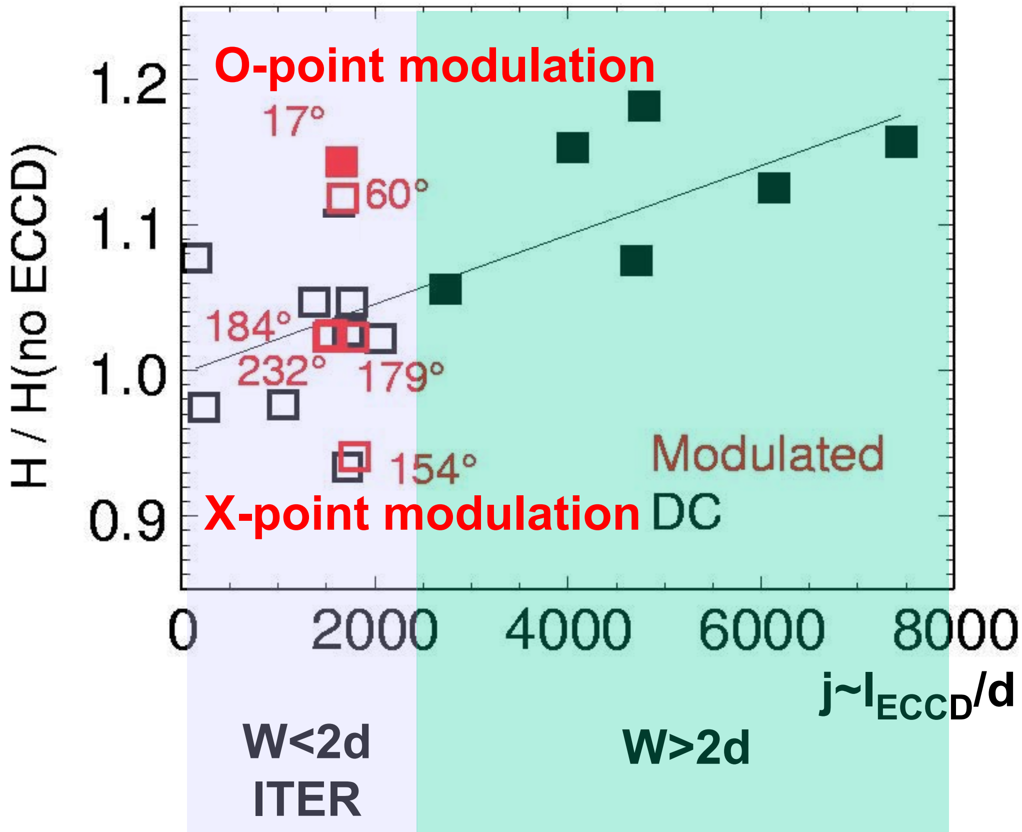
- **narrow deposition W>2d:**
  - I_{ECCD} counts for helical CD
  - full stabilisation with dc ECCD of (3,2) and (2,1) NTMs
  - no advantage of phased ECCD

- **broad deposition W<2d:**
  - mimics ITER $W_{marg} \sim \rho^*$
  - I_{ECCD}/d^2 counts for dc ECCD
  - only partial dc stabilization
  - required current increases significantly

⇒ modulated ECCD required (at mode frequency / O-point injection)

NTM stabilization: **Modulated ECCD with broad deposition**

Confinement improvement



Zohm EX/4-1Rb

High-Z wall and divertor in ITER / DEMO

pro: - tritium co-deposition with carbon
- erosion of low-Z material
- neutron bombardment destructs graphite

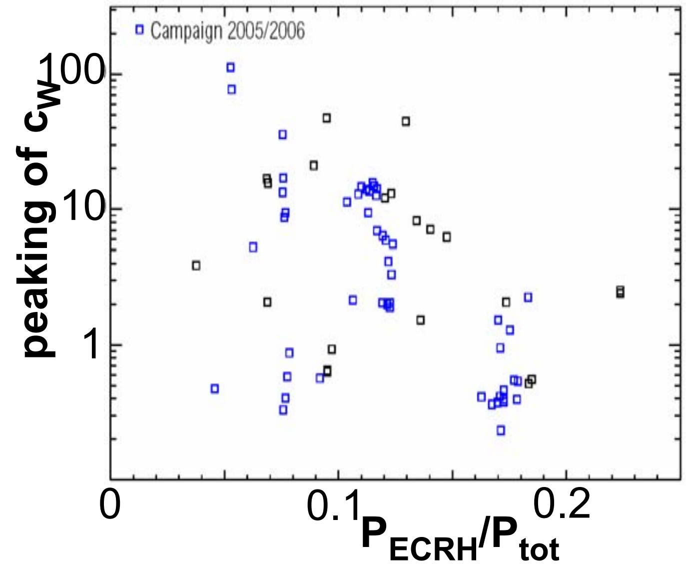
} ITER }DEMO

con: - central radiation losses sets limit c_W< some 10^{-5}

Sputtering source mainly from LFS limiters

Dux EX/3-3Ra

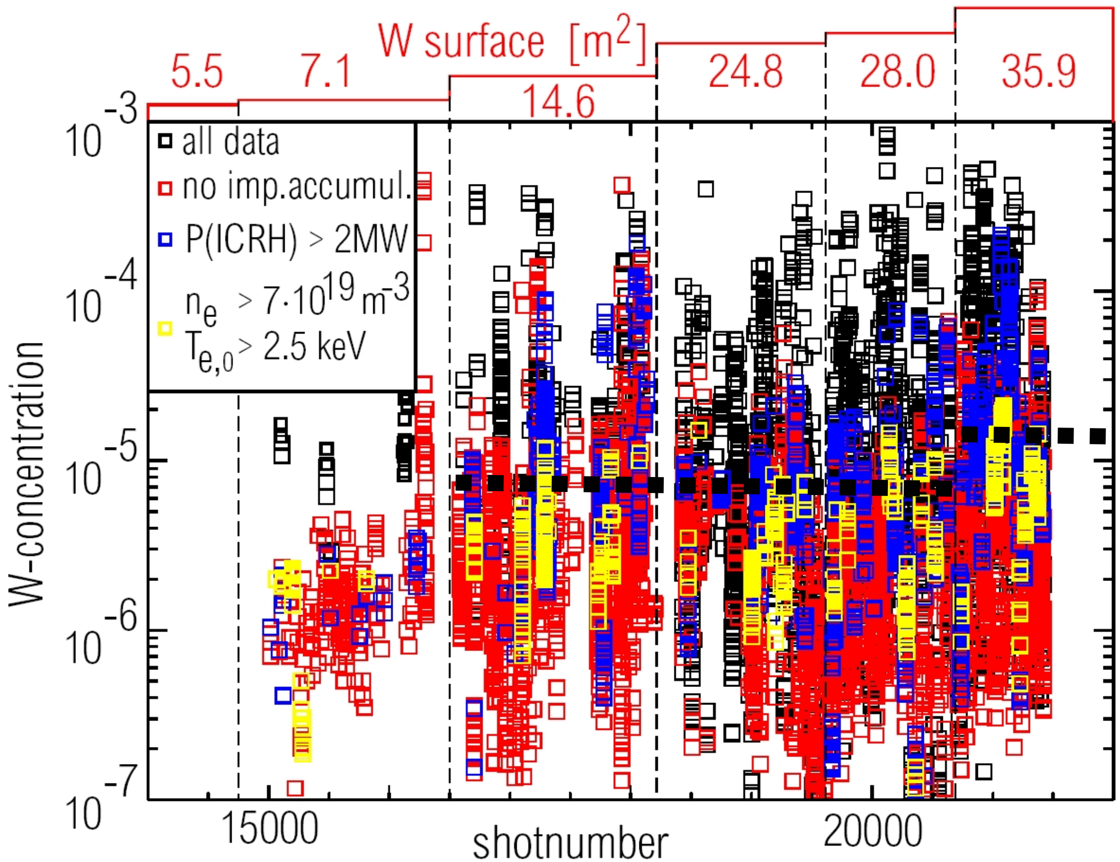
- CX neutrals ←T_e(edge)
- fast ions from NBI: depends on injection geometry
- • antenna limiters with ICRH: 60-90% of W influx
  - sheath rectified E-fields accelerate impurities
- drastic enhancement of all sources during ELMs



Impurity transport

- H-mode barrier
  →ELM frequency control by pellet injection
- neoclassical inward pinch
- anomalous outward impurity transport
  enhanced by central heating (ICRH, ECRH)

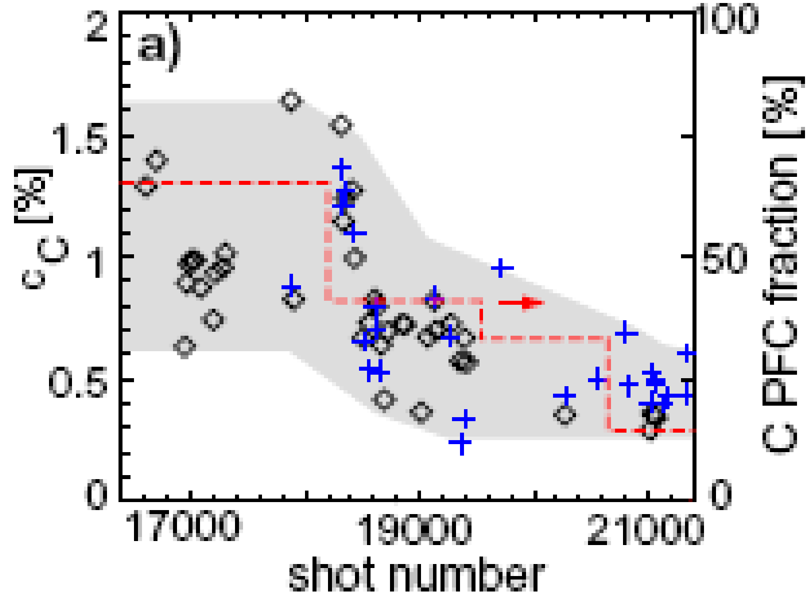
W wall: **Long term evolution of W concentration**



- wide distribution depending on plasma conditions: increase with W coverage, saturation of mean value around 10^{-5}
- reduced c_W at relevant central heating power and higher densities (ITER!)

W wall: **Indications for transitions to W device**

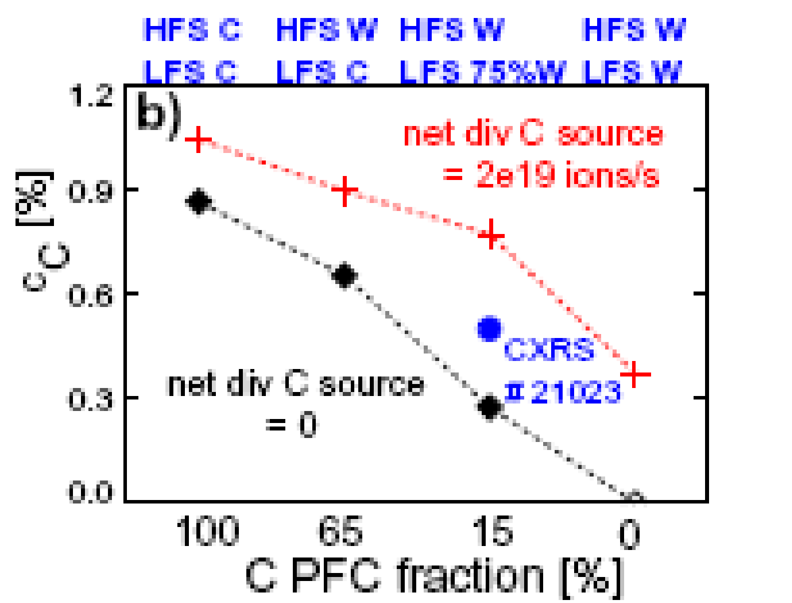
- reduction of C plasma content
  (standard H-mode discharge)



- Migration / transport model
  - slow evolution due to strong C recycling
  - C ‚leaking' out of divertor important

    $1 \cdot 10^{19}$ atoms/s

  → remaining strong net erosion zone



Dux EX/3-3Ra

Noble gas retention / release:
Schmid EX/3-3Rb

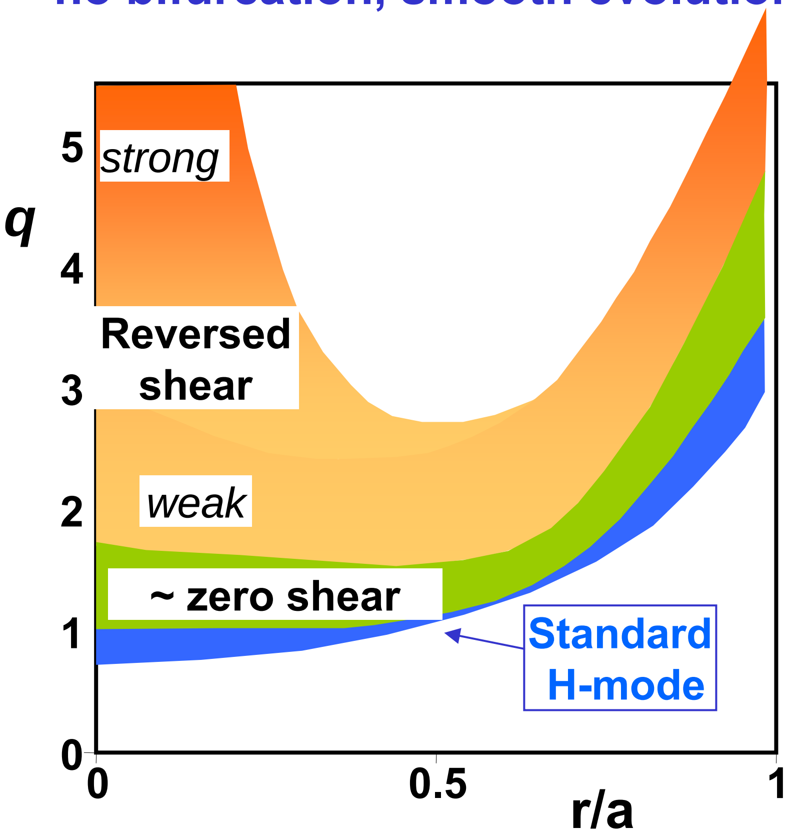
Improved H-mode: **Characterization of „advanced scenarios"**

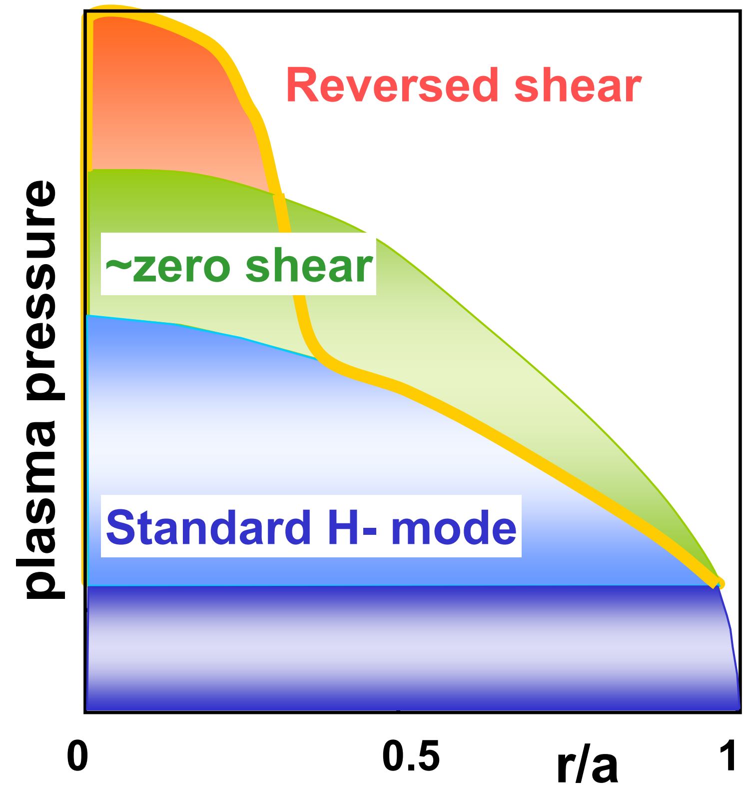
Zero shear, 'hybrid' discharges:

- elevated q(0) above 1 desirable
- **stationary with $\beta_N H/q_{95}^2$ up to 0.4**
- **high β-limit close to no wall limit**
- **substantial bootstrap fraction ≤ 50%**
- **no bifurcation, smooth evolution**

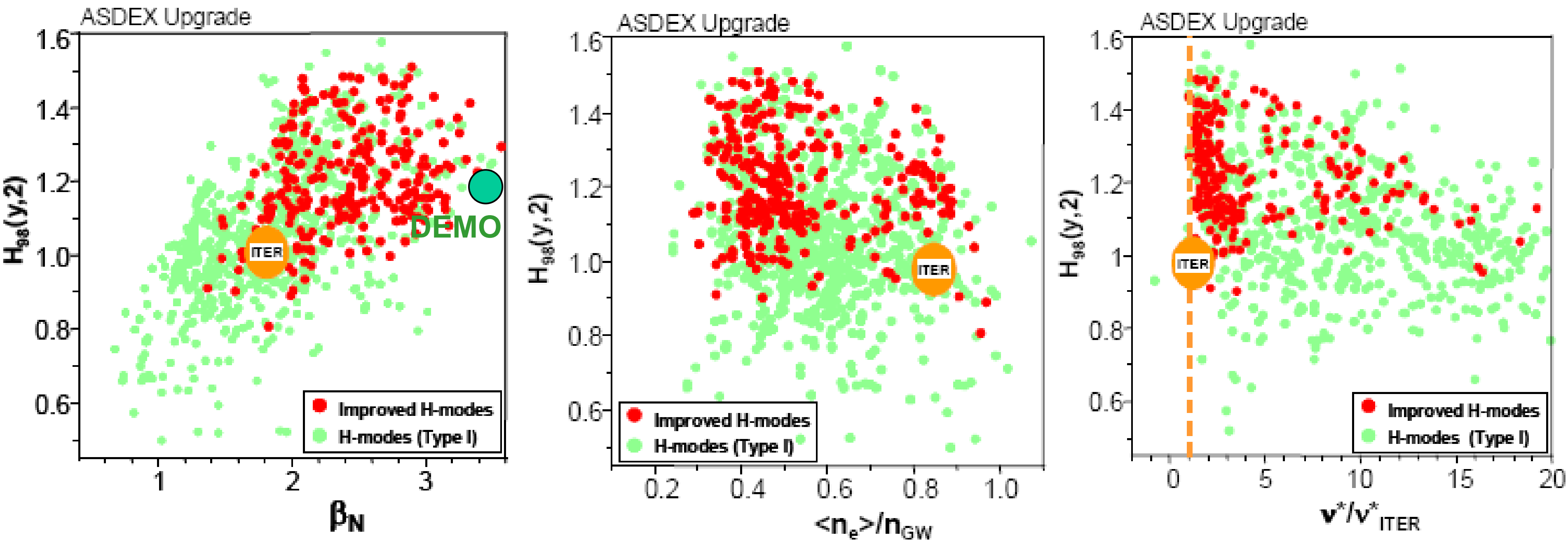
Reversed shear, ITB discharges:

- hollow current profile
- **high $\beta_N H/q_{95}^2$>0.25 only transient**
- control of pressure and current delicate
- high bootstrap fraction > 60% → **ss**
- transport bifurcation





Improved H-mode: **Performance and operational range**



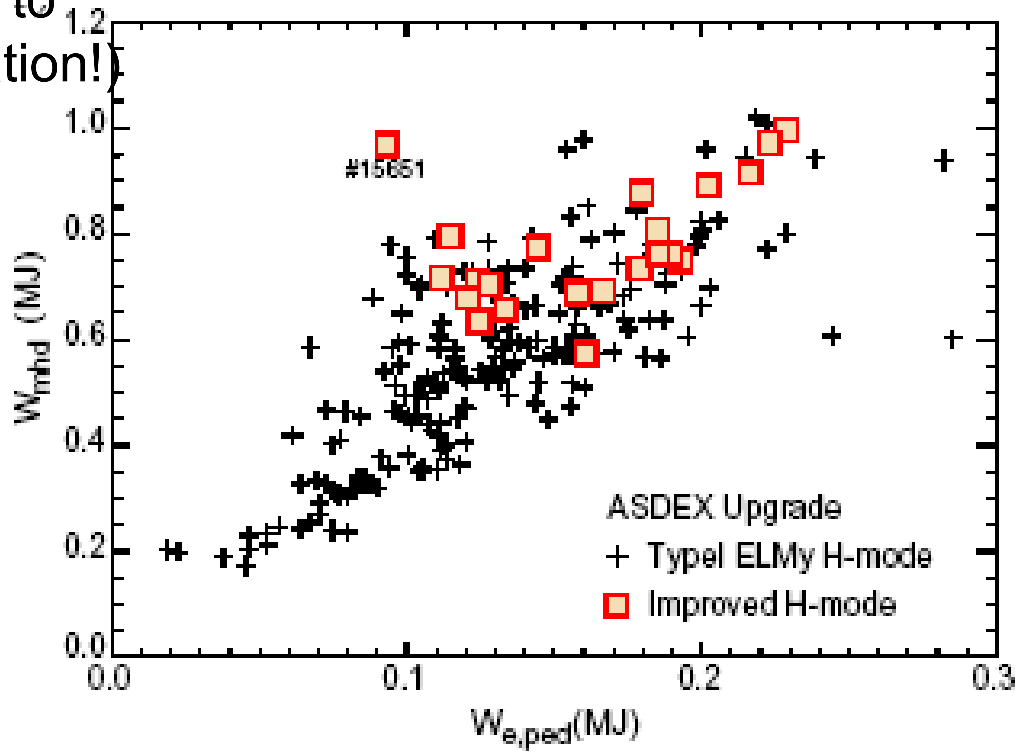
similar correlation of density peaking to ν^*

Sips EX/1-1, Weisen EX/8-4

- β_N = 2-3.3 and $H_{98(y,2)}$ =1-1.5
- β_N above 3 achievable at q_{95}=3-5
- operating at ITER collisionality and at densities close to Greenwald
- stationary on several current diffusion times

Improved H-mode: **Confinement**

- heat transport given by TEM/ITG turb.
  - stiff temperature profile
  - plasma energy connected with pedestal pressure (pedestal energy)
- confinement improvement weakly correl. with more peaked density profiles
  - flatter density profiles anyway due to central heating (impurity accumulation!)

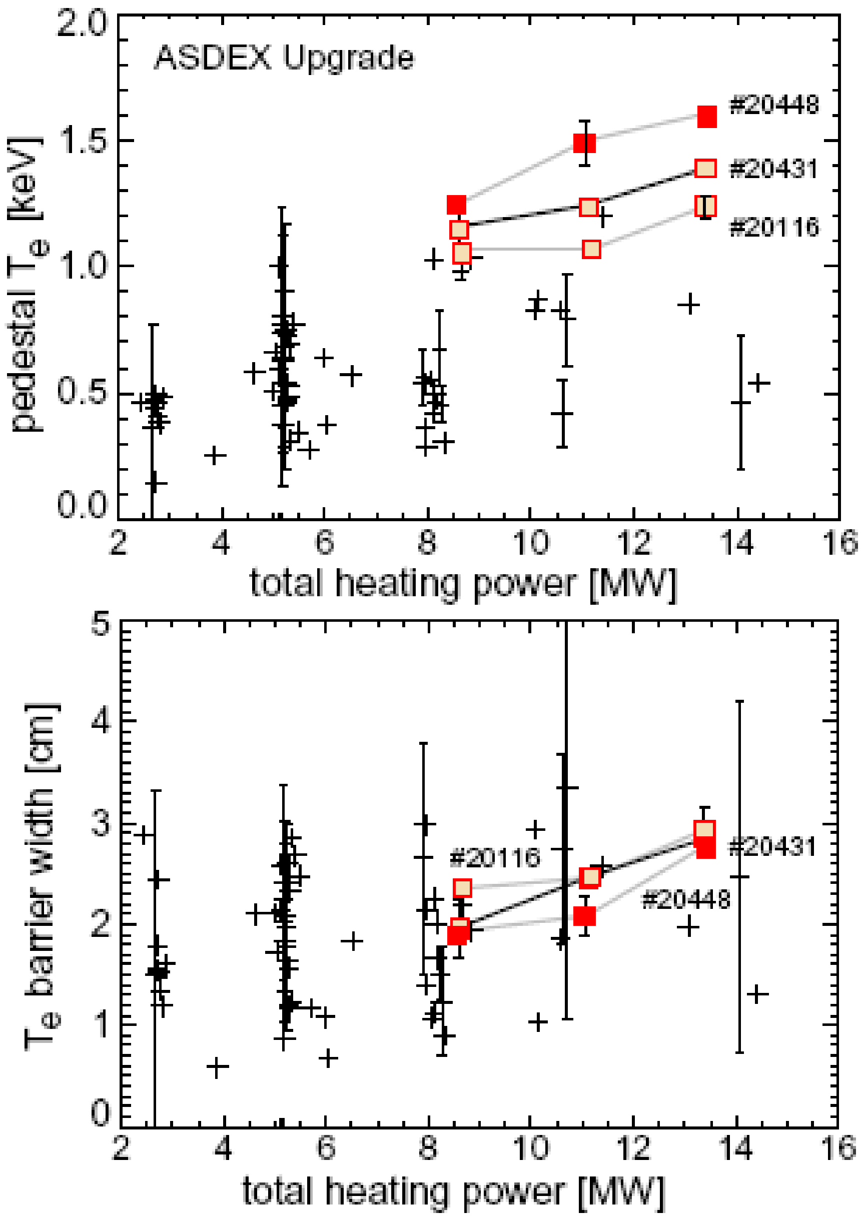


Suttrop EX/8-5

Improved H-mode: **Confinement**

- heat transport given by TEM/ITG turb.
  - stiff temperature profile
  - plasma energy connected with pedestal pressure (pedestal energy)
- confinement improvement weakly correl. with more peaked density profiles

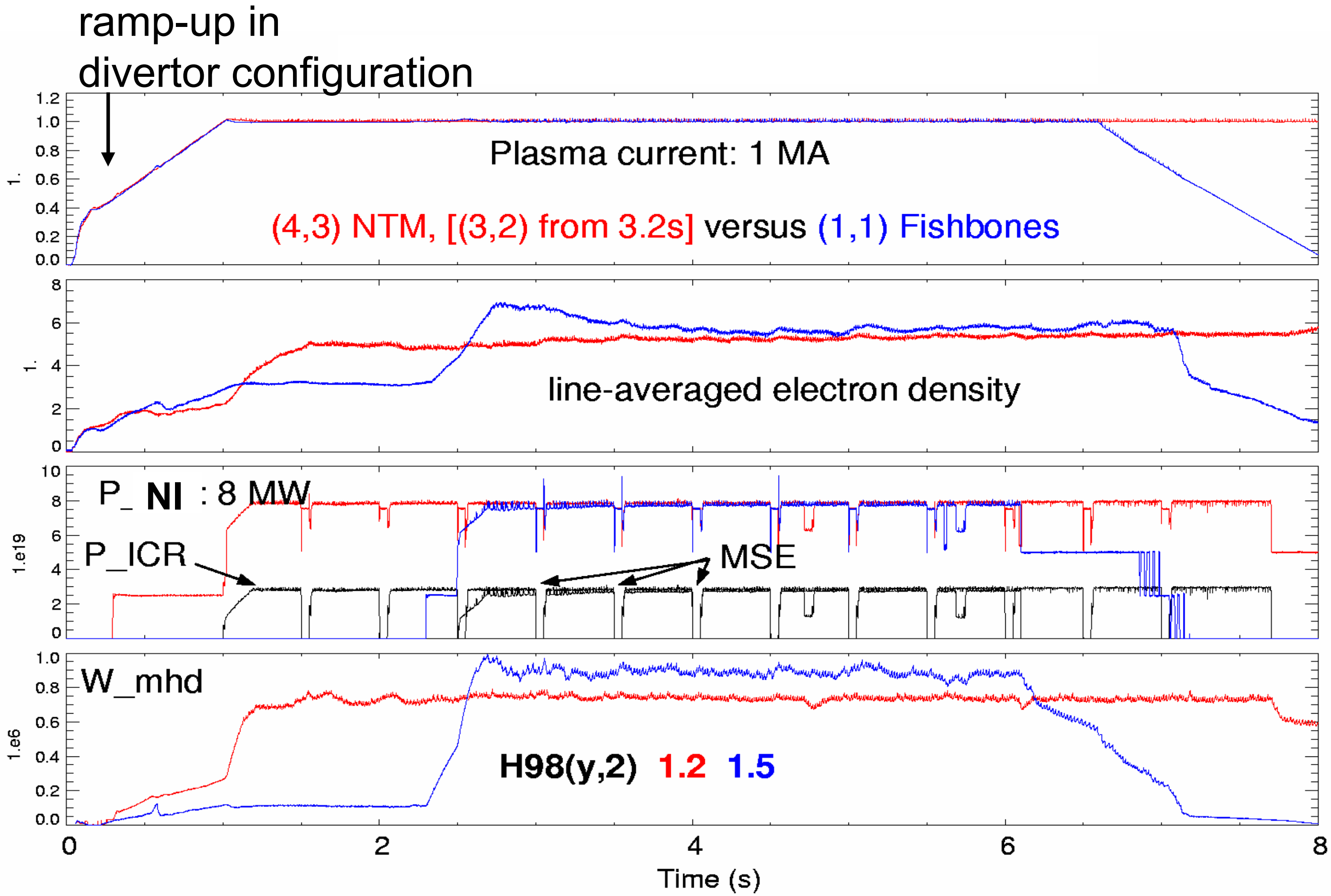
- pedestal top pressure enhanced
  - increases stronger than $P_{add}^{0.3}$
  - predominantly $T_{e,i}$ rise due to broader barrier width
  - $\nabla p_{barrier} \approx$ const.



Suttrop EX/8-5, Maggi IT/P1-6,

Improved H-mode: **Scenario development**

- early versus late heating: **performance increase**



q_{95}≈4.8

$T_{e,i}(0)$≈5.2 keV

$T_{e,i}(0)$≈4.5 keV

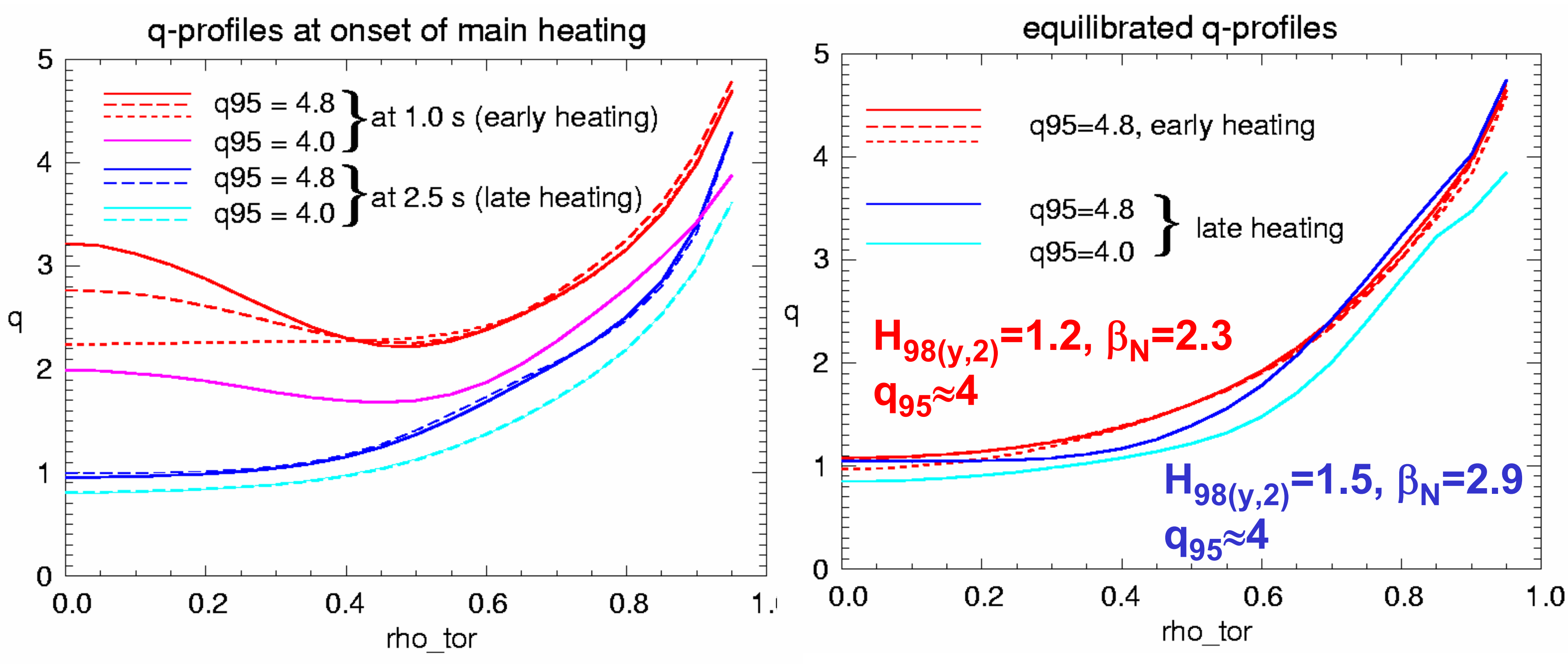
β_N and $H_{98(y,2)}$ differences disappear at higher heating powers

Stober EX/P1-7

Improved H-mode: **Influence of q-profile**

- Scenarios with limiter /divertor ramp-up, early / late heating:

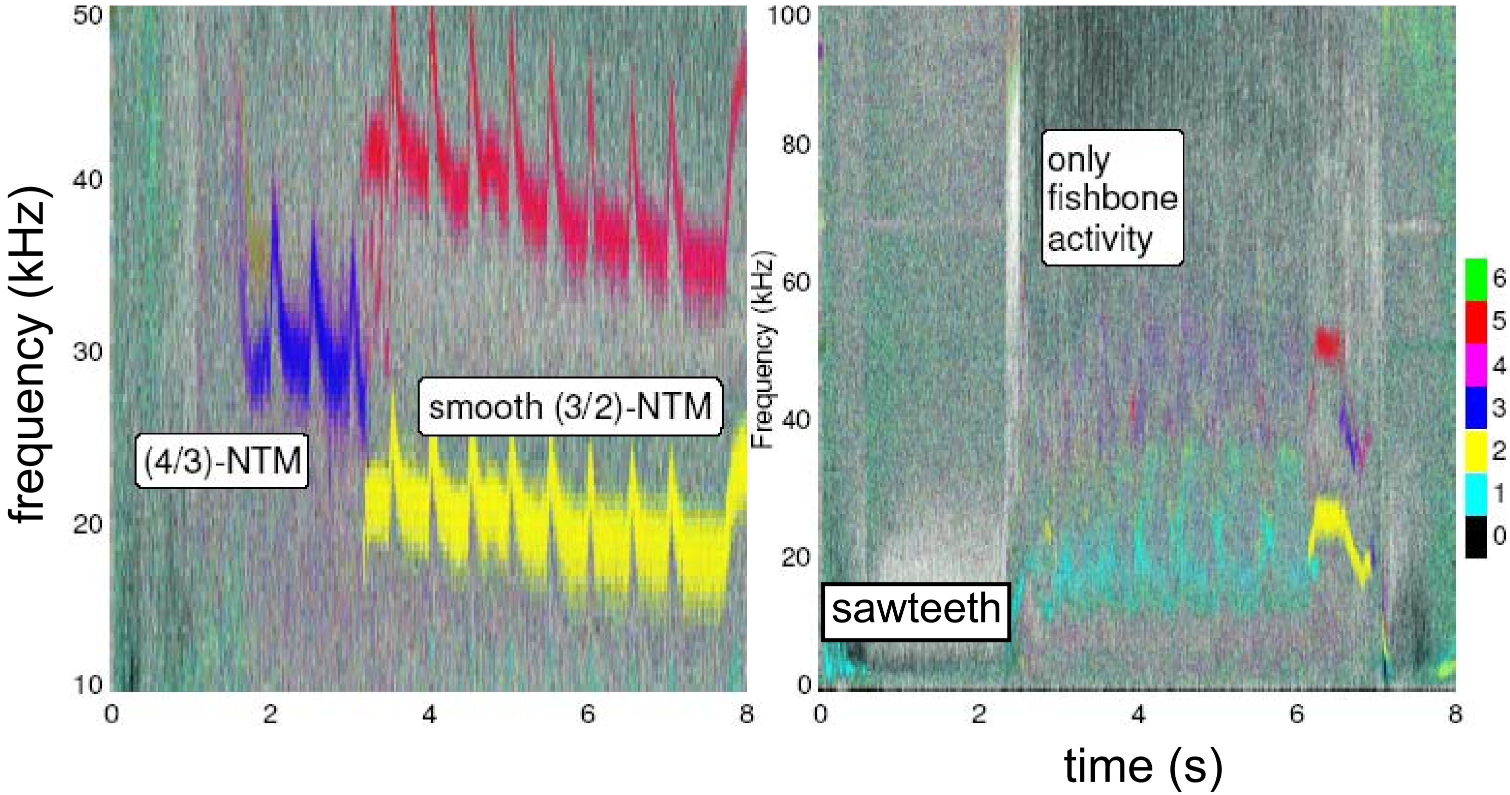
effect on q profile



Stober EX/P1-7

Improved H-mode: **Influence of q-profile**

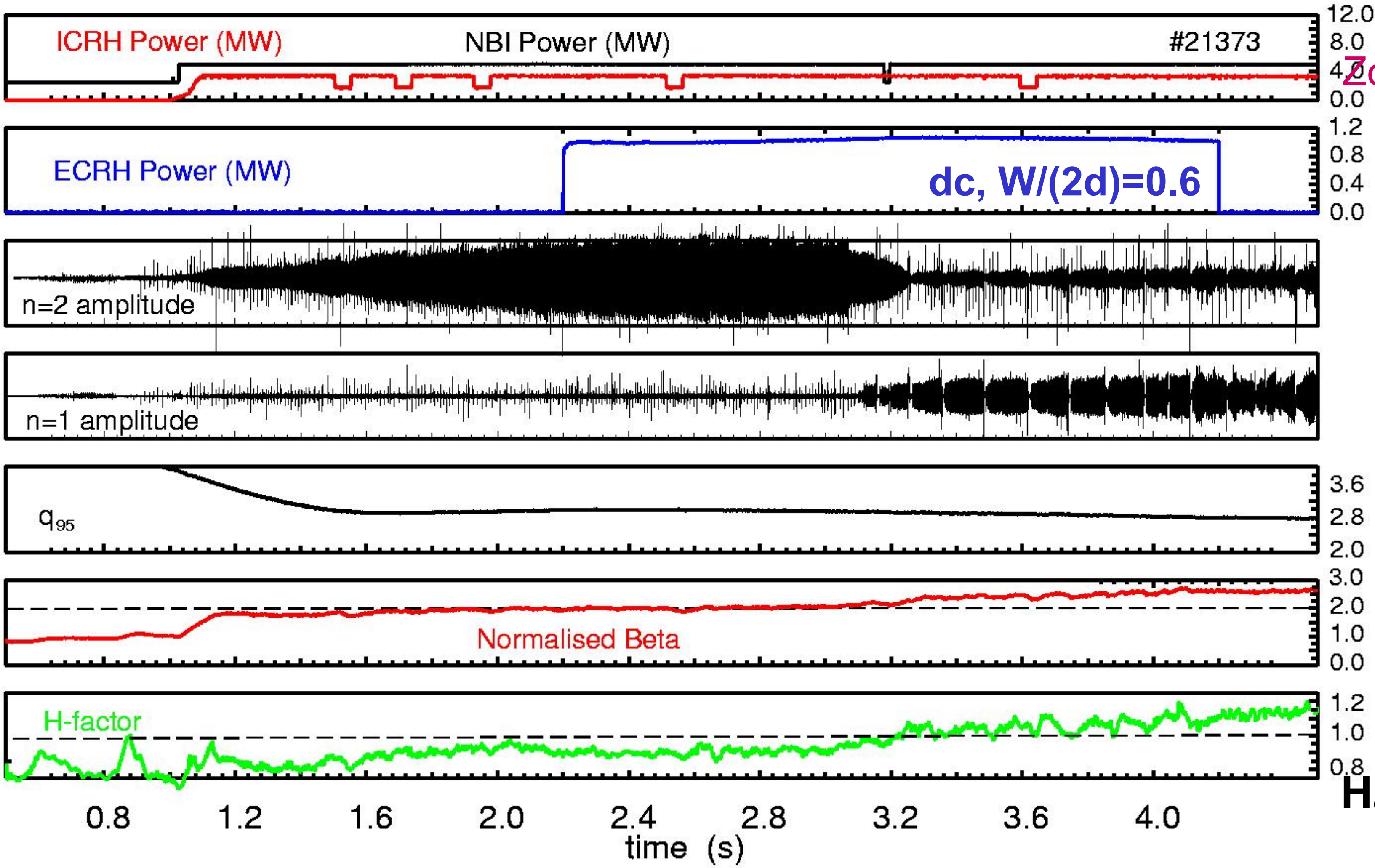
- **different MHD behaviour: both clamp the current profile**
  - slightly peaked current profile
  - flat central current profile



- **influence on transport:** - theory tells us $R/L_{Ti} \sim s/q$
  - both quantities up to 25% enhanced for flat q-profile
  - in agreement with threshold from GS2 ($\gamma_{max}=\omega_{ExB}$)
- edge pressure increased in case with flatter q-profile

Stober EX/P1-7

Improved H-mode: **(3,2) NTM suppression with ECCD**



Sips EX/1-1

Zohm EX/4-1

q_{95}=2.9

β_N≈2.6

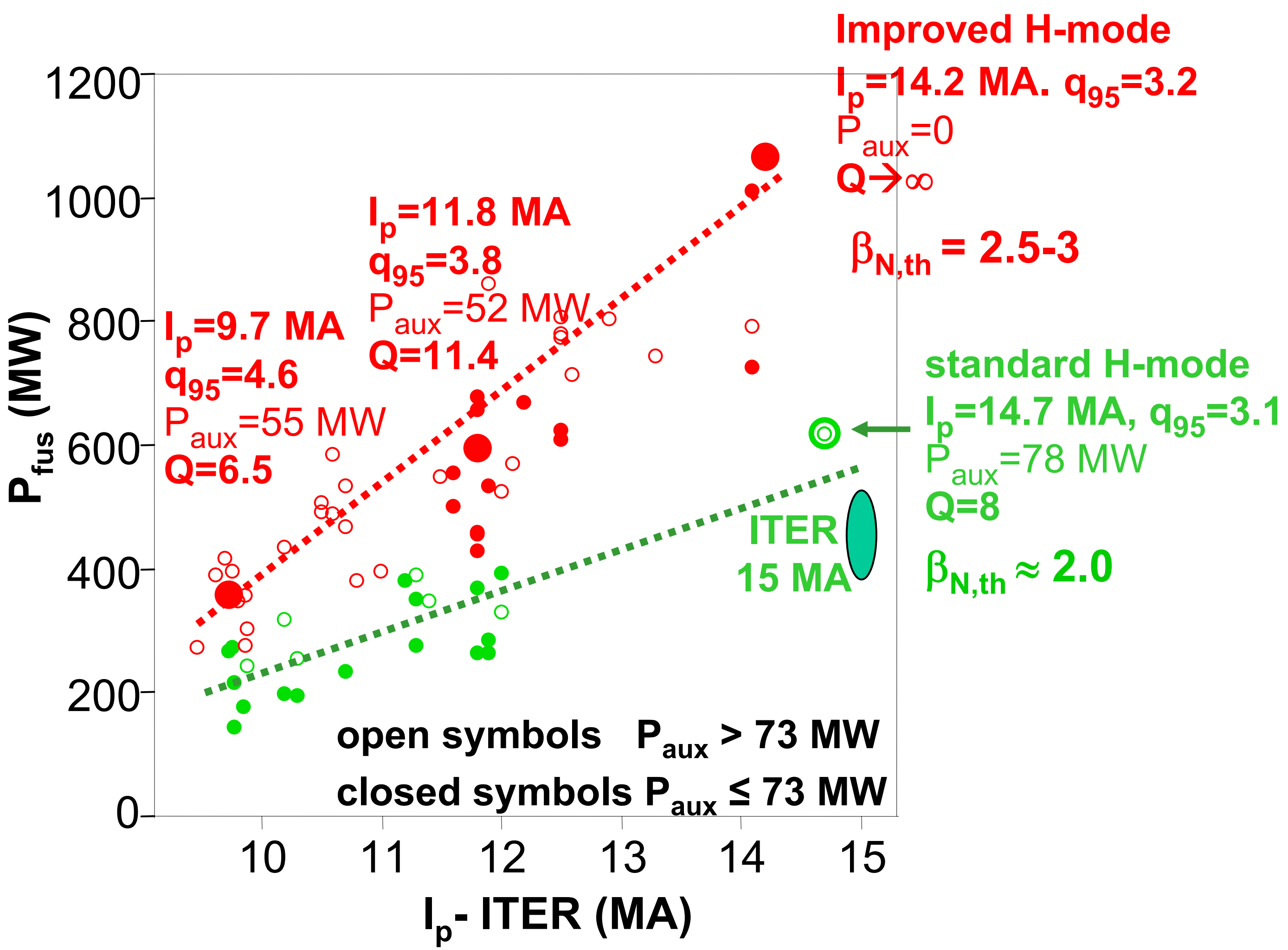
$H_{98(y,2)}$≈1.2

- at low q95<3.5 large (3,2) NTM can develop → strong impact on confinement
- after stabilization transition to fishbone activity → enhanced performance

Improved H-mode: **predictions for ITER**

Extrapolation to ITER using AUG kinetic profile shapes and IPB98(y,2) scaling

q_{95}, β_N as in AUG, $\langle n \rangle / n_{GW}=0.85$, $T_e=T_i \rightarrow$ $\mathbf{P_{fus}}$ → $\mathbf{P_{aux}, Q}$



Sips EX/1-1

Substantial progress for the benefit of ITER was achieved.

- AUG focuses on integrated ITER scenarios and performance beyond reference
- Understanding of anomalous transport and turbulence (TEM,ITG) proceeds:
  ITER: peaked density profiles and benign high-Z accumulation to be expected
- Fast ions: - losses caused by MHD and anomalous diffussion important
  - off-axis NBCD above a certain turbulence level questionable
- Modulated ECCD needed for NTM stabilization of ITER reference scenario
- ELM (pacemaking) and disruption mitigation (gas injection) schemes evolve
- high-Z walls compatible with tokamak operation modes
  - impurity sputtering source by ICRF accelerated impurities critical
  - accumulation control by ELMs and central heating (α-particles) afforded
- Improved H-mode / Hybrid scenario guides ITER beyond reference scenario
  - ITER parameter range achieved (q_{95}, ν^*, n_e/n_{GW}) at $H_{98(y,2)}$=1.1-1.5 and β_N=2.5-3.5
  - $Q \rightarrow \infty$ and prolonged pulse length at full current (q_{95}=3)
  - Q=10 and 1 h pulses at reduced current ($q_{95} \geq 4$)
  - heating power of 73 MW may not be sufficient to achieve $\beta_N \approx 3$ for IPB98(y,2)

Future AUG hardware extensions

- Internal coils
  - besides RWM control many other applications (f=1/10 kHz); 2007-9
  - compatibility w. RWM control;
  - compatibility with heating systems
  - diagnostic access (YAG,...);
  - relevant diagnostic development
- ICRH antenna fitting to shell

  installation befor shell mounting ?
- LHCD 2008-10

  → 5 MW at 3.7 GHz; 200 kA off-axis CD

  hardware and manpower from Associations needed
- Stabilising shell 2009-10

AUG contributions to this conference

- **Main aim is to establish the physics base for ITER (and DEMO):**
  - consolidation of the 'standard' H-mode scenario
  - exploration of ‚advanced' modes beyond standard scenario

Pereverzev FT/P5-23

- **Understanding of physics elements**
  - **transport** Angioni EX/8-5Rb, Conway EX/2-1, Jenko EX/8-5Ra, Weisen EX/8-4
  - **fast particles and NBCD** Günter EX/6-1, McCarthy TH/P3-7
  - **H-mode edge and ELM tailoring** Neuhauser EX/P8-2, Chankin TH/P6-15, Scott TH/1-1
  - **disruption mitigation** Pautasso EX/P8-7
  - **MHD control with ECCD** Zohm EX/4-1Rb, Yu TH/P3-13, Merkel TH/P3-8
  - **tungsten wall and divertor** Dux EX/3-3Ra, Schmid EX/3-3Rb
- **Integration into improved scenario beyond reference**
  - **Improved H-mode (Hybrid scenario)** Sips EX/1-1, Suttrop EX/8-5, Stober EX/P1-7, Maggi IT/P1-6,