ASDEX Upgrade

Max-Planck-Institut für Plasmaphysik

IPP

Recent ASDEX Upgrade Research in Support of ITER and DEMO

Hartmut Zohm

for the ASDEX Upgrade /EUROfusion MST1 Team*

MPI für Plasmaphysik, Garching, Germany

**see list at the end of the talk*

- ASDEX Upgrade: machine and programme
- Edge: H-mode access and pedestal physics
- Core: transport and MHD stability
- Exhaust: operation at high P_{sep}/R and $P_{rad,core}/P_{tot}$
- Scenario development

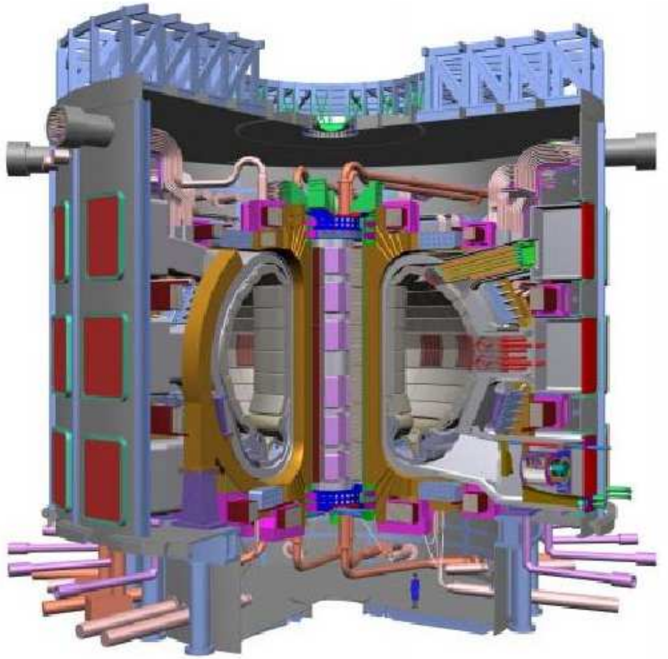
IAEA Fusion Energy Conference, OV2/2, St. Petersburg, Russia, 13.10.2014

Outline

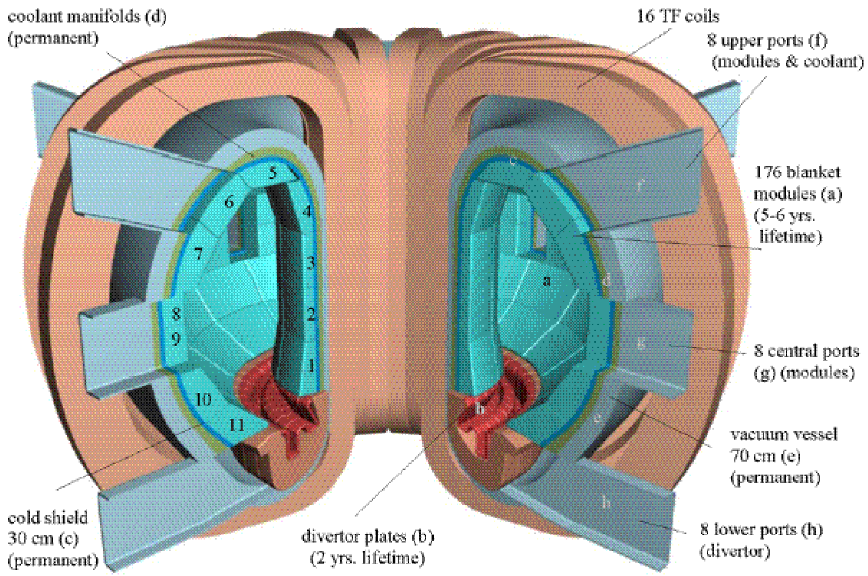
- ASDEX Upgrade: machine and programme
- Edge: H-mode access and pedestal physics
- Core: transport and MHD stability
- Exhaust: operation at high P_{sep}/R and $P_{rad,core}/P_{tot}$
- Scenario development

AUG Programme in support of ITER and DEMO

ITER



DEMO (example)



Q=10: β_N=1.8, H=1, n/n_{GW}=0.85

P_{sep}/R = 15 MW/m, $P_{rad,core}/P_{tot}$=0.3

Large type I ELMs not allowed

Very small number of disruptions

Q≥30: β_N=3.5, H=1.2, n/n_{GW}=1.2

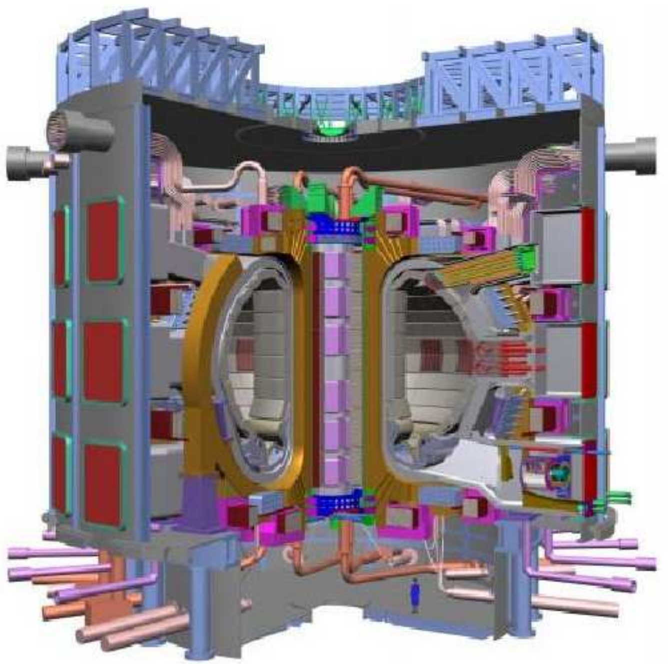
P_{sep}/R = 15 MW/m, $P_{rad,core}/P_{tot}$=0.75

No ELMs allowed (?)

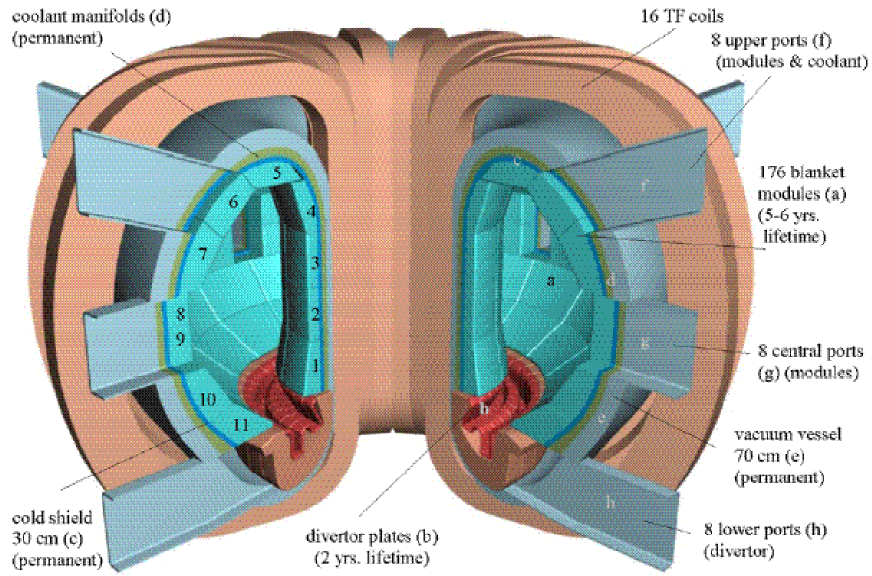
Virtually no disruptions

AUG Programme in support of ITER and DEMO

ITER



DEMO (example)



Q=10: β_N=1.8, H=1, n/n_{GW}=0.85

P_{sep}/R = 15 MW/m, $P_{rad,core}/P_{tot}$=0.3

Large type I ELMs not allowed

Very small number of disruptions

Q≥30: β_N=3.5, H=1.2, n/n_{GW}=1.2

P_{sep}/R = 15 MW/m, $P_{rad,core}/P_{tot}$=0.75

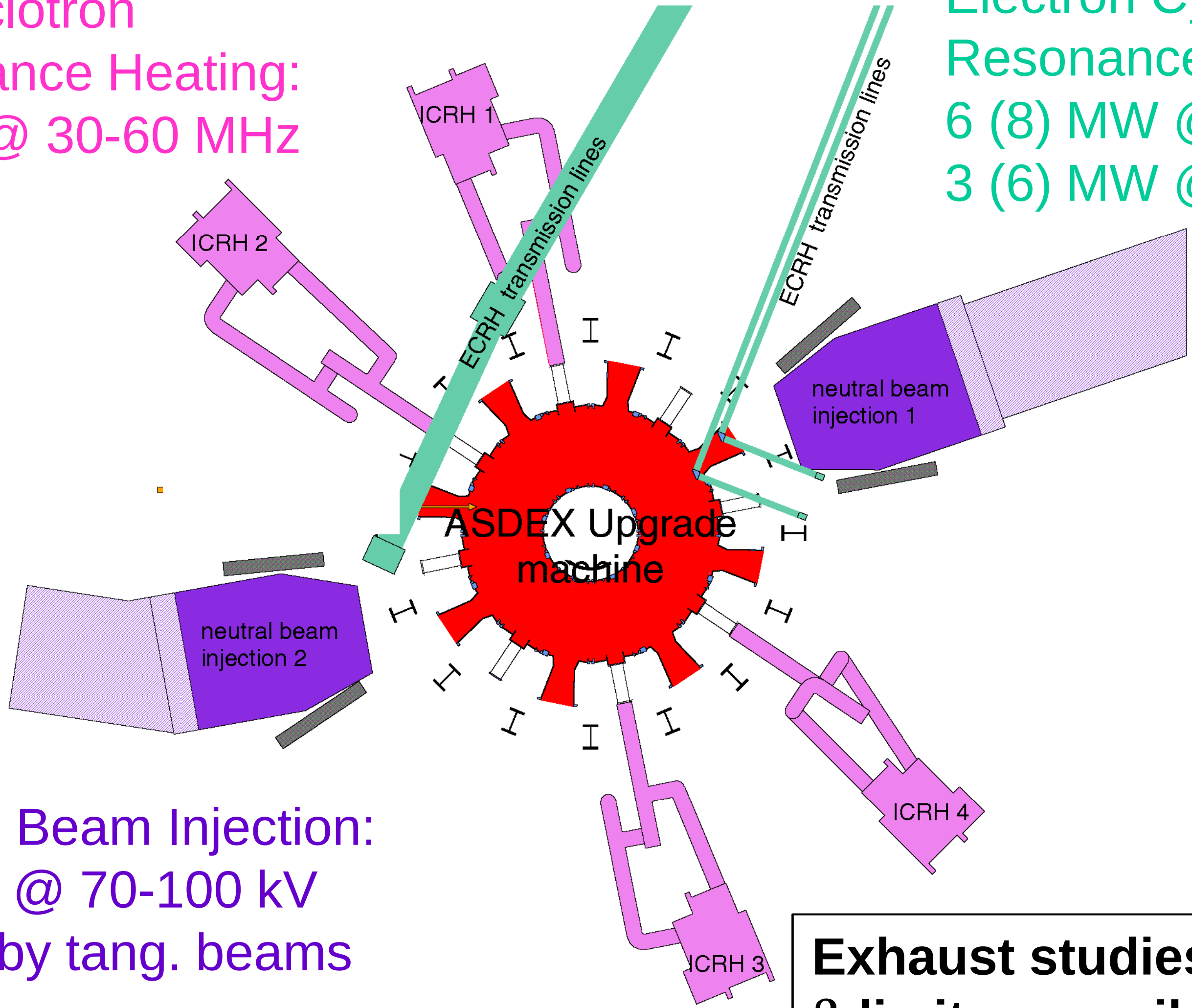
No ELMs allowed (?)

Virtually no disruptions

ASDEX Upgrade has a powerful H&CD system

Ion Cyclotron
Resonance Heating:
8 MW @ 30-60 MHz

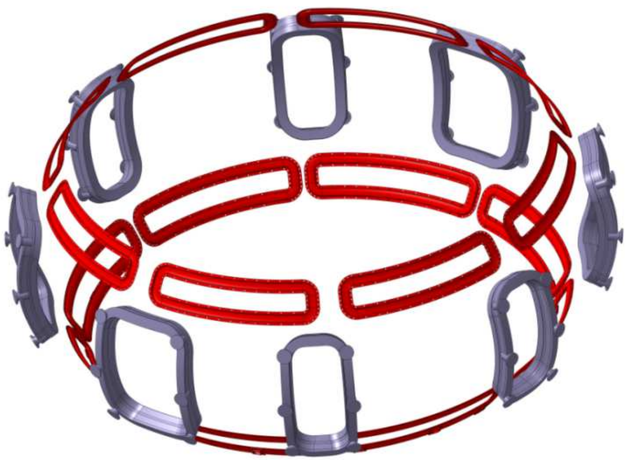
Electron Cyclotron
Resonance Heating:
6 (8) MW @ 140 GHz
3 (6) MW @ 140/105 GHz

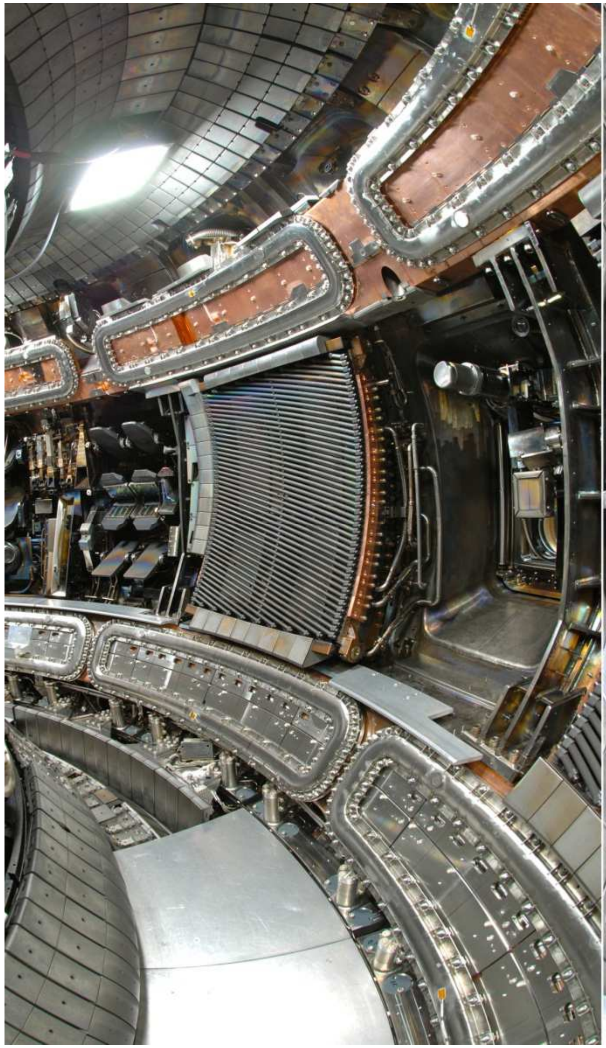


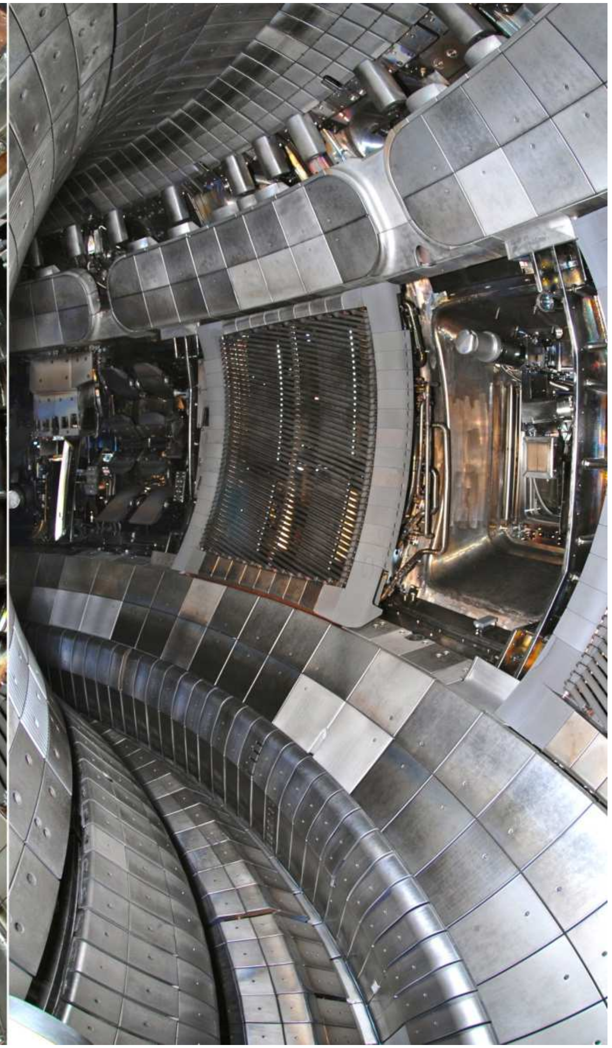
Neutral Beam Injection:
20 MW @ 70-100 kV
NBCD by tang. beams

Exhaust studies at high P/R
β-limit accessible at any field
ECCD for MHD control

2 x 8 off-midplane saddle coils for MHD control

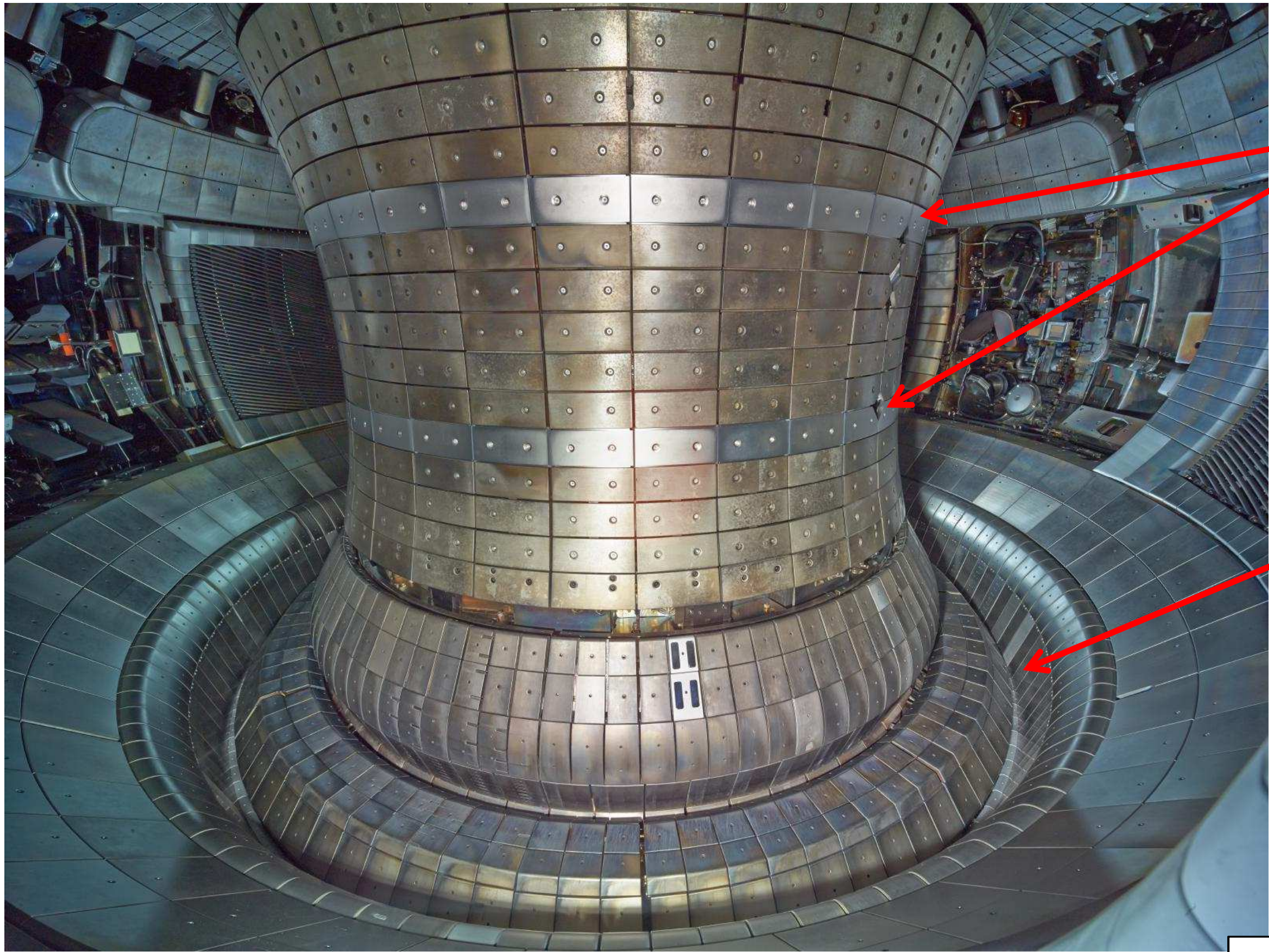






New: rotating fields up to 150 Hz, continuous poloidal phase scan at constant *n*

Massive outer W-divertor and Bare Steel Tiles



P92 tiles (chemistry and ferromagnetism similar to EUROFER)

(iron mostly saturated, typical μ_r =1.7)

massive tungsten tiles

Both enhancements performed reliably without problem during 2014 campaign

A. Herrmann et al., this conference

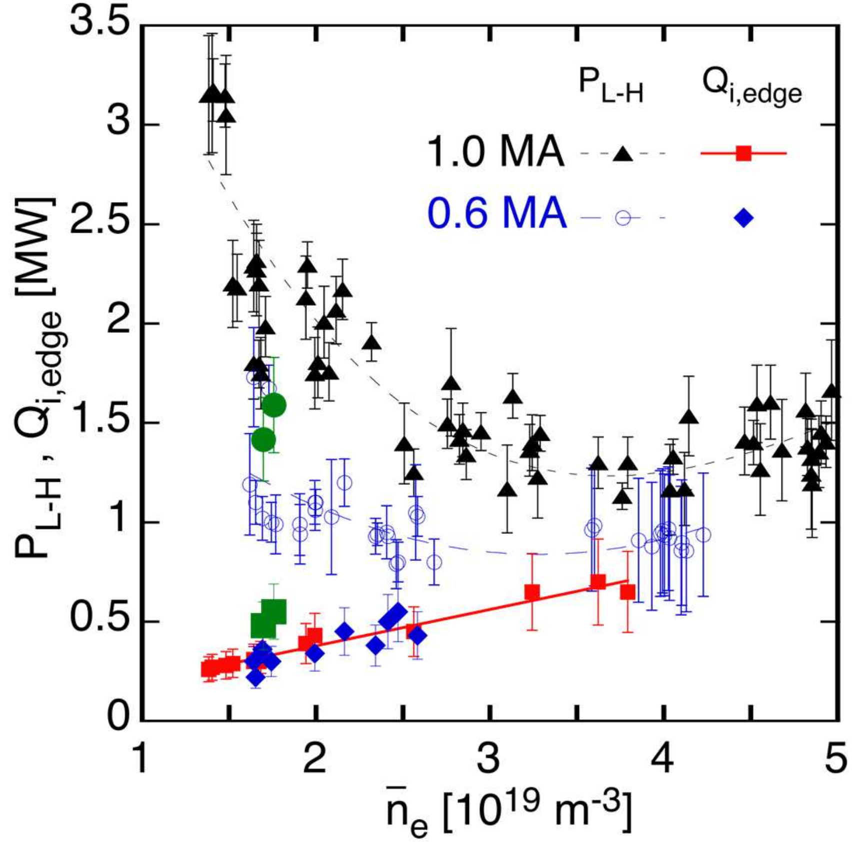
+ switchable liquid He valve for reduction of pumping (high power scenarios)

+ new divertor manipulator allowing large area sample insertion

Outline

- ASDEX Upgrade: machine and programme
- Edge: H-mode access and pedestal physics
- Core: transport and MHD stability
- Exhaust: operation at high P_{sep}/R and $P_{rad,core}/P_{tot}$
- Scenario development

H-mode operation: low density limit



F. Ryter et al., Nucl. Fusion 2014

Increase of P_{LH} at low density disappears when plotted versus q_i

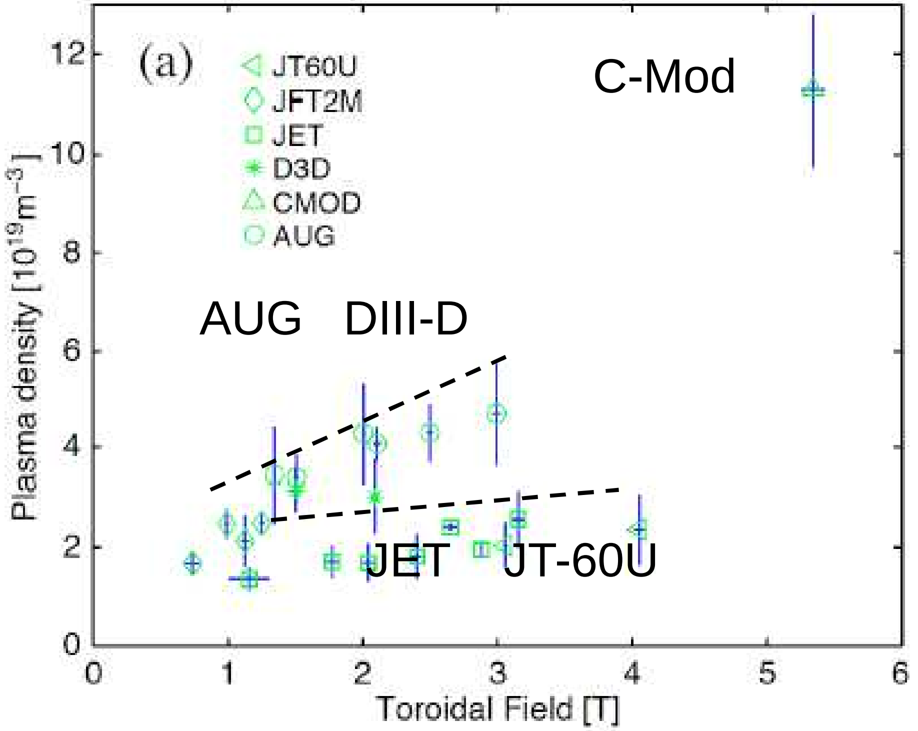
- points towards q_i being main ingredient for edge E_r
- unifies current and heating type dependence at low density

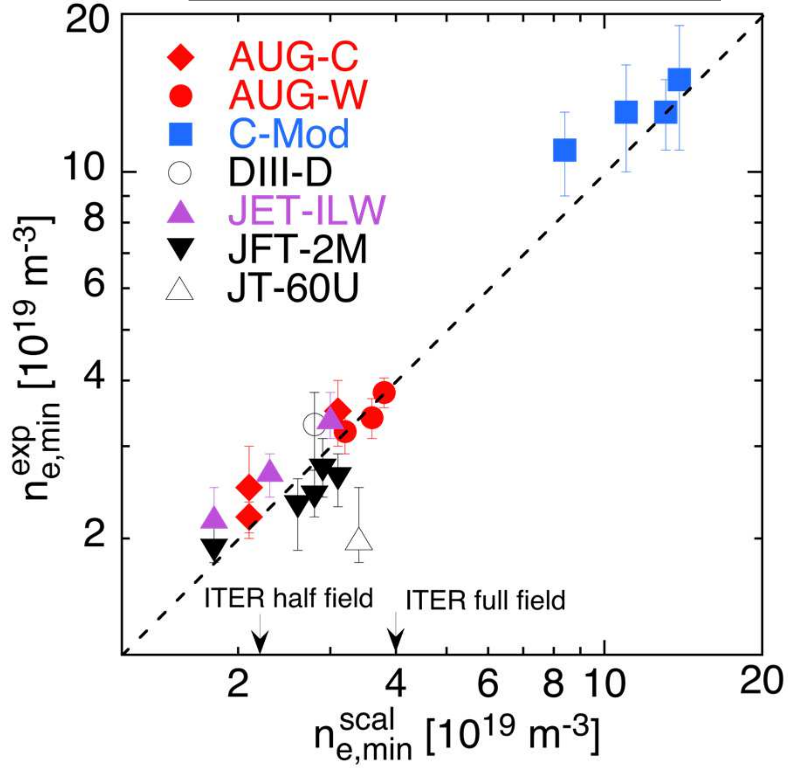
$$E_r \approx \frac{\nabla p_i}{e n_i}$$

Reminder: P_{LH} about 20% lower with all-metal wall, also seen on JET

H-mode operation: low density limit

F. Ryter et al., Nucl. Fusion 2014





Transition to low density branch governed by e-i coupling

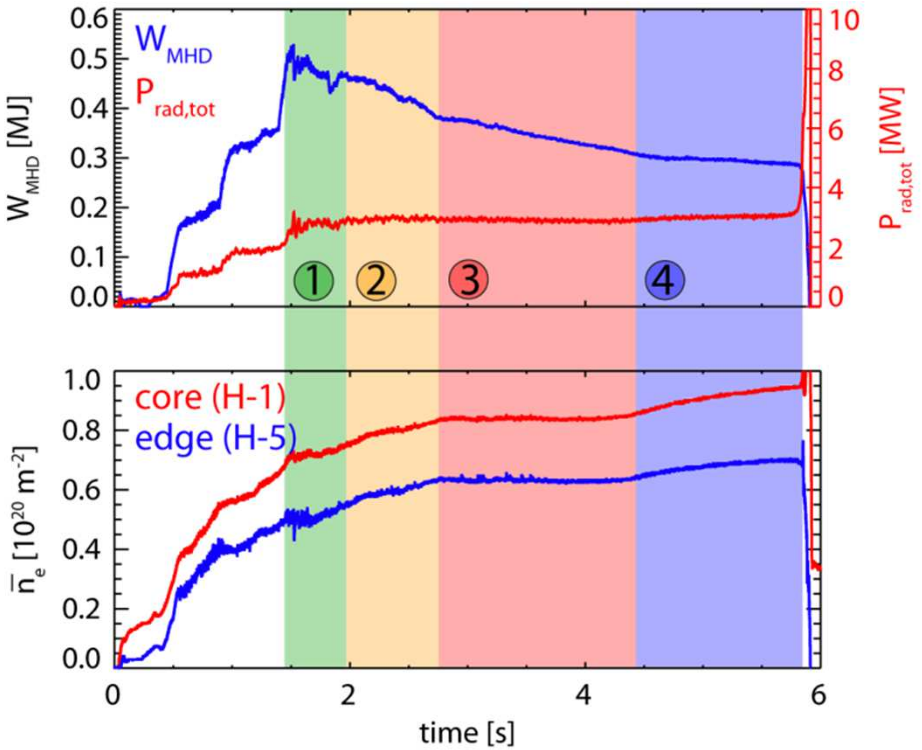
- assume that $\tau_{ei} / \tau_E \approx$ const. at $n_{e,min}$

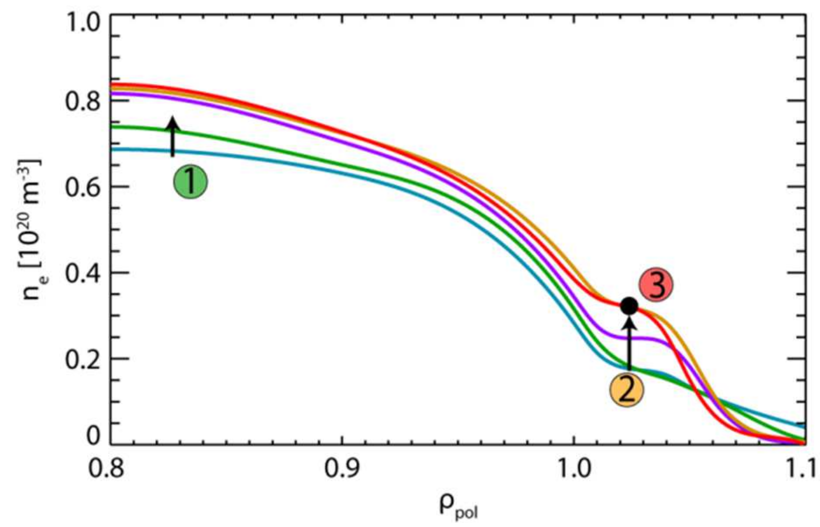
$$n_{e,\min}^{scal} = 0.7 I_p^{0.34} a^{-0.95} B_T^{0.62} (R/a)^{0.4}$$

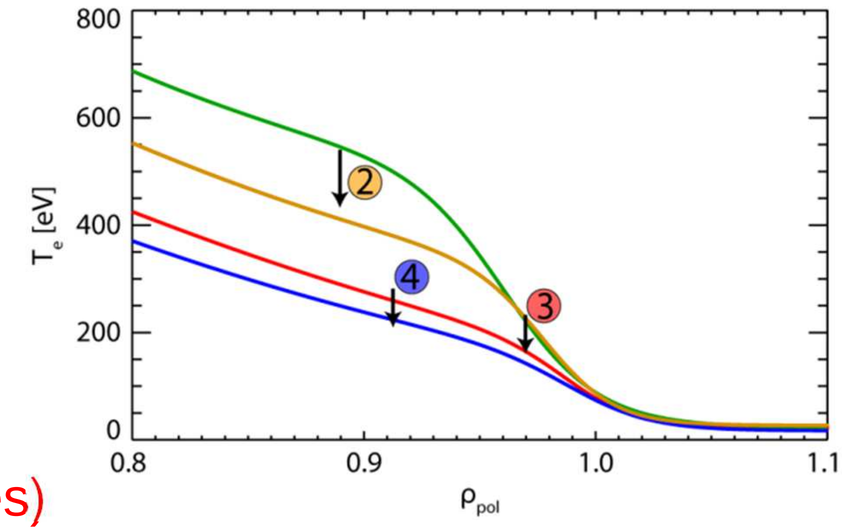
- inserting τ_E- and (medium density) P_{LH}-scalings leads to $n_{e,min}$ scaling

Scaling unifies experimental data, predicts ITER to be in linear regime

H-mode operation: high density limit







1: 'Normal' H-mode (density ↑)

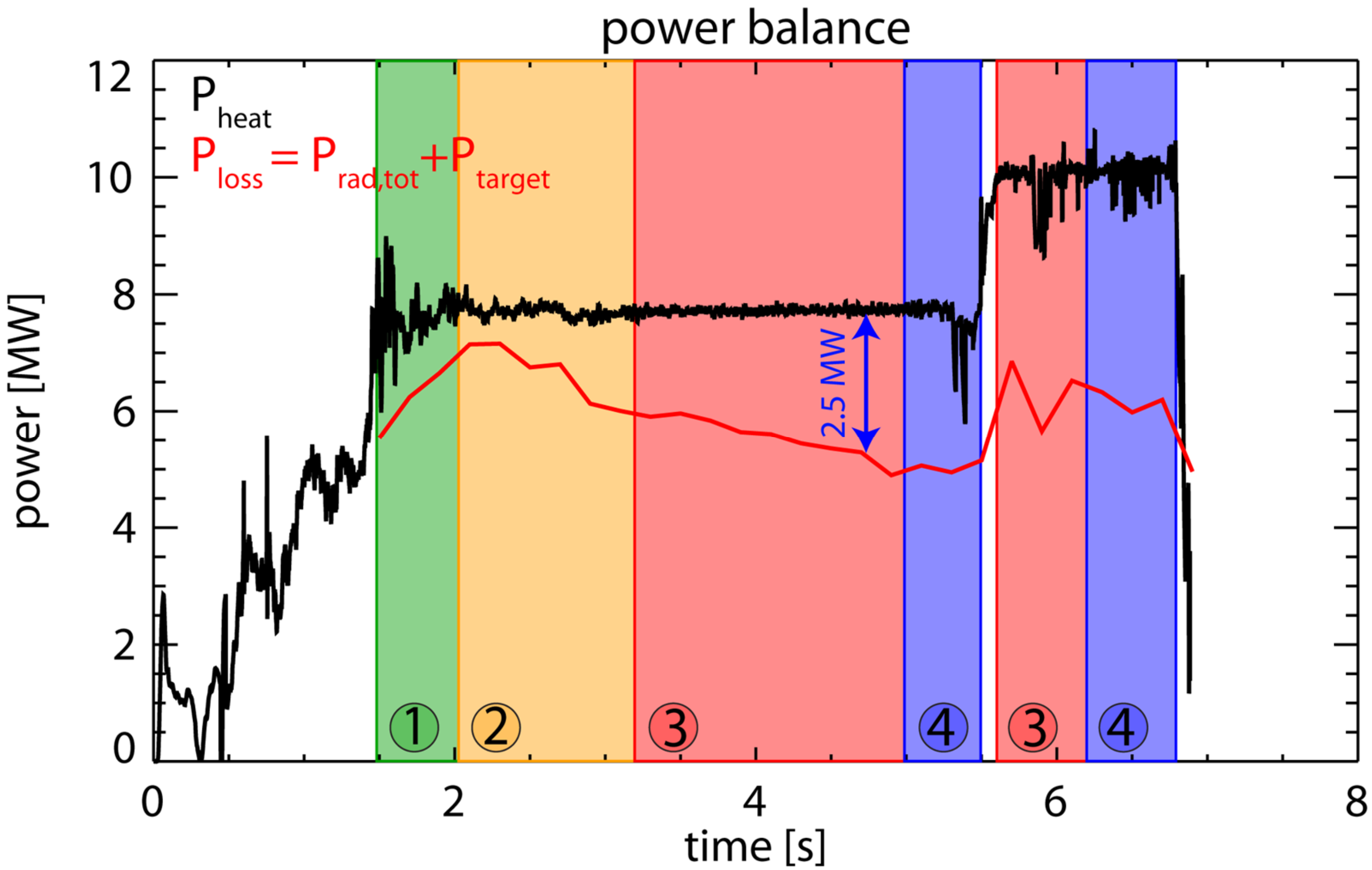
2: degrading H-mode (only SOL ↑)

3: H-mode breakdown (pedestal erodes)

4: L-mode (density ↑, MARFE, disruption)

M. Bernert et al., EPS 2014, to appear in PPCF

H-mode density limit by combination of 2 effects

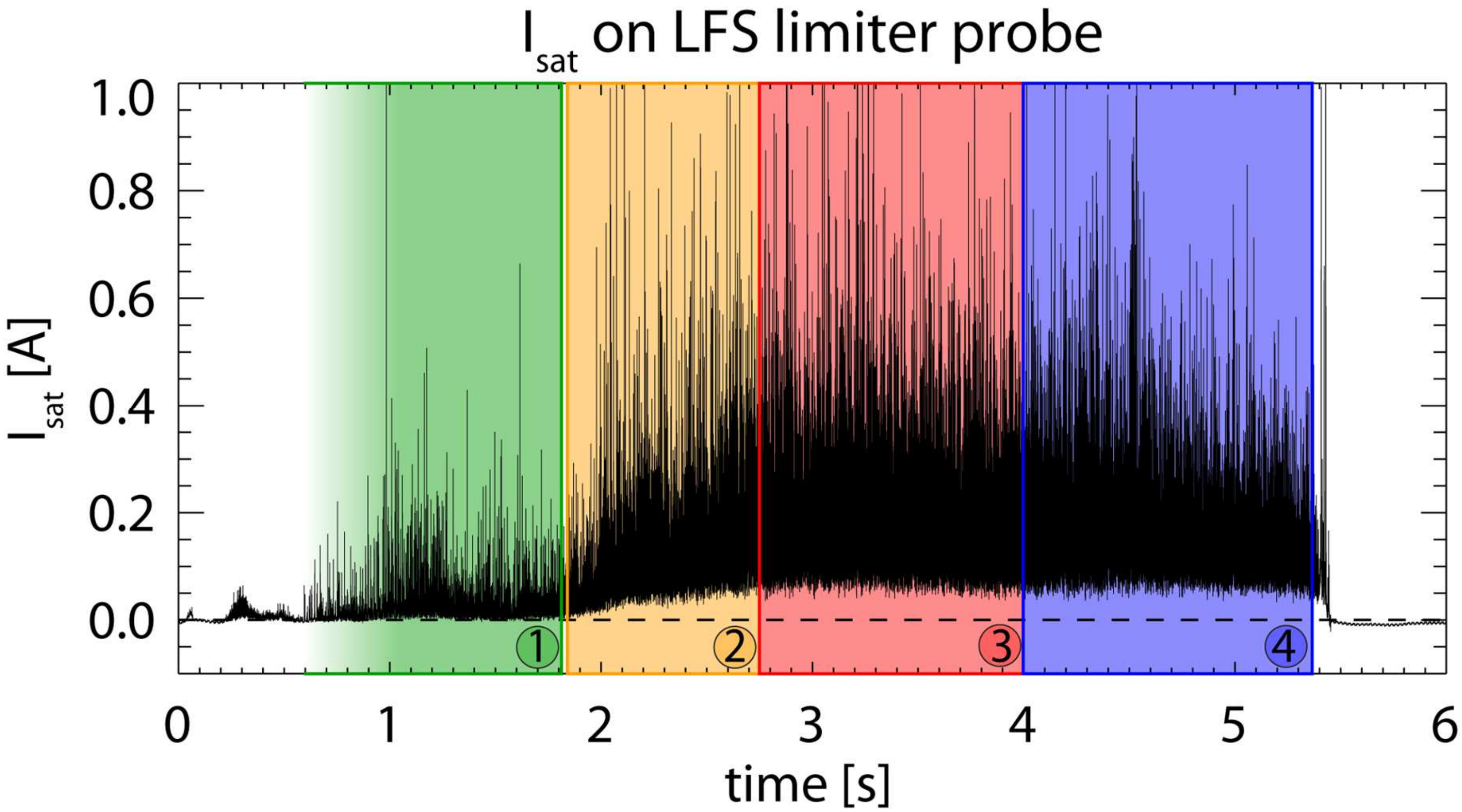


Stagnation of core density build-up due to fuelling limit (source shifts to SOL)

High SOL density leads to strong filamentary transport there

- changed boundary condition at target can increase filament velocity

H-mode density limit by combination of 2 effects

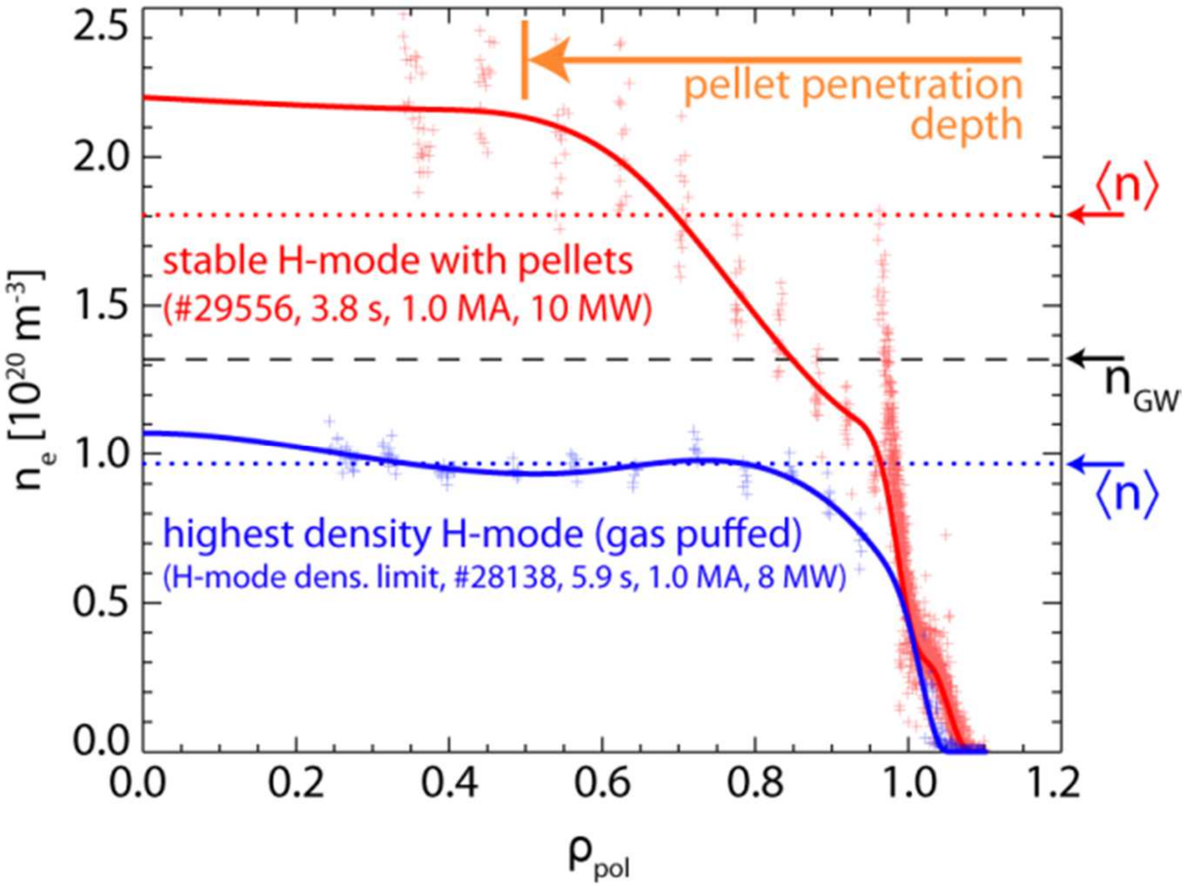


Stagnation of core density build-up due to fuelling limit (source shifts to SOL)

High SOL density leads to strong filamentary transport there

- changed boundary condition at target can increase filament velocity

H-mode operation at $n/n_{GW} > 1$



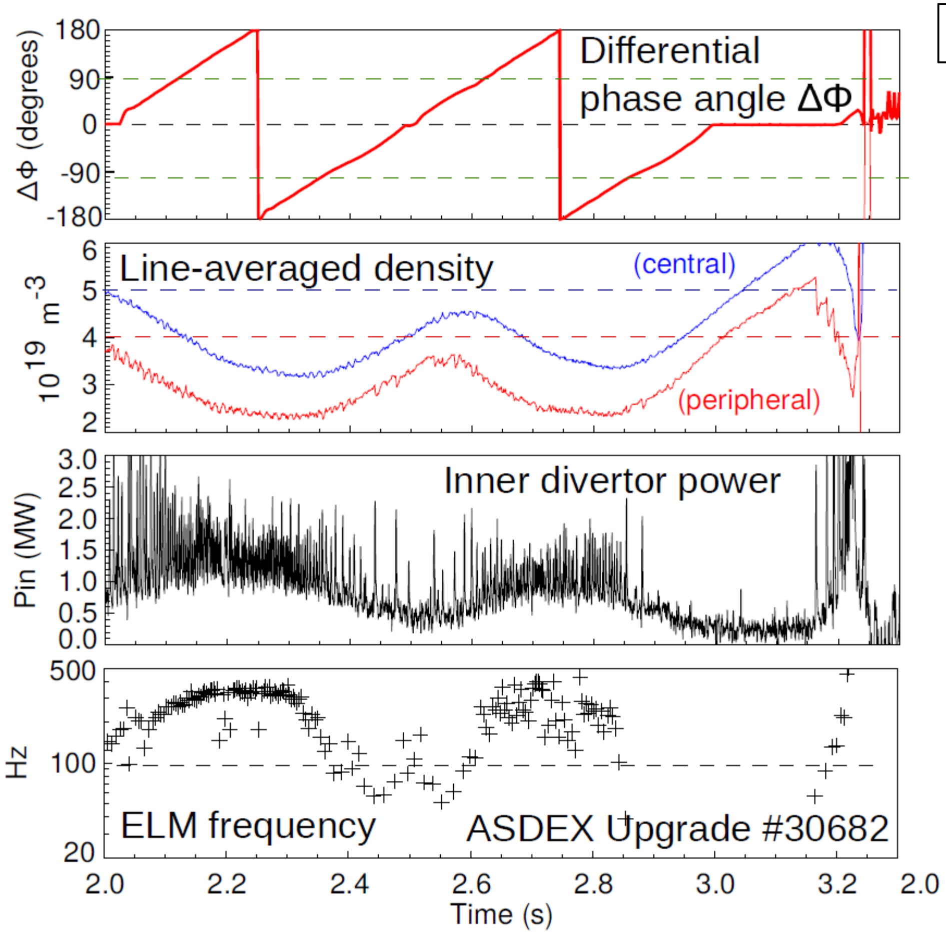
Edge density stays below n_{GW} even with pellets at $n = 1.5\ n_{GW}$

For DEMO: expect strong low collisionality anomalous particle pinch

- DEMO might be able to operate above $n > n_{GW}$

H-mode operation: ELM Mitigation at low ν*

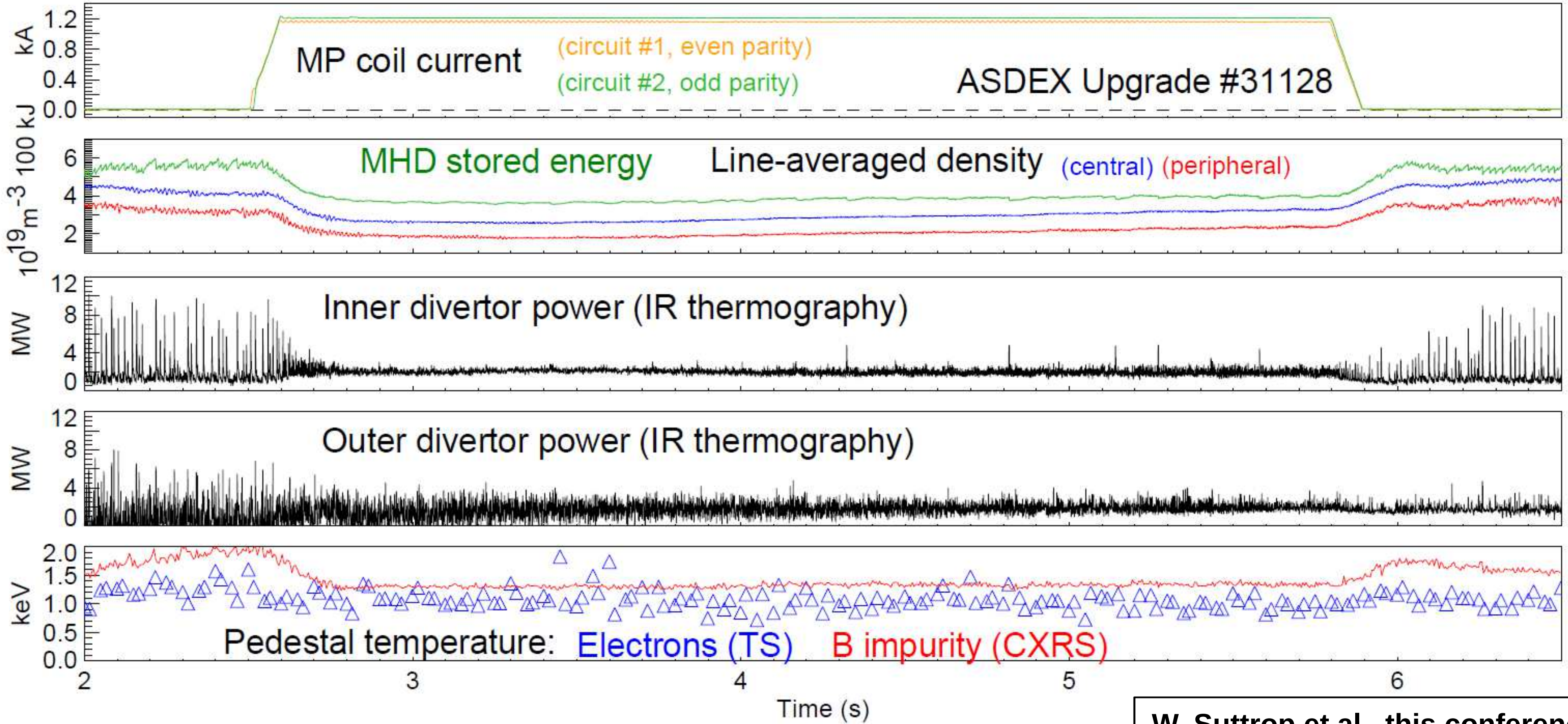
W. Suttrop et al,, this conference



Contrary to high ν*-branch, poloidal spectrum is important

- best ELM mitigation coincides with strongest density pumpout
- note: also ‘classical’ ELM-free phase can be triggered

H-mode operation: ELM Mitigation at low ν*



W. Suttrop et al,, this conference

At optimum phasing, significant type ELM mitigation is observed

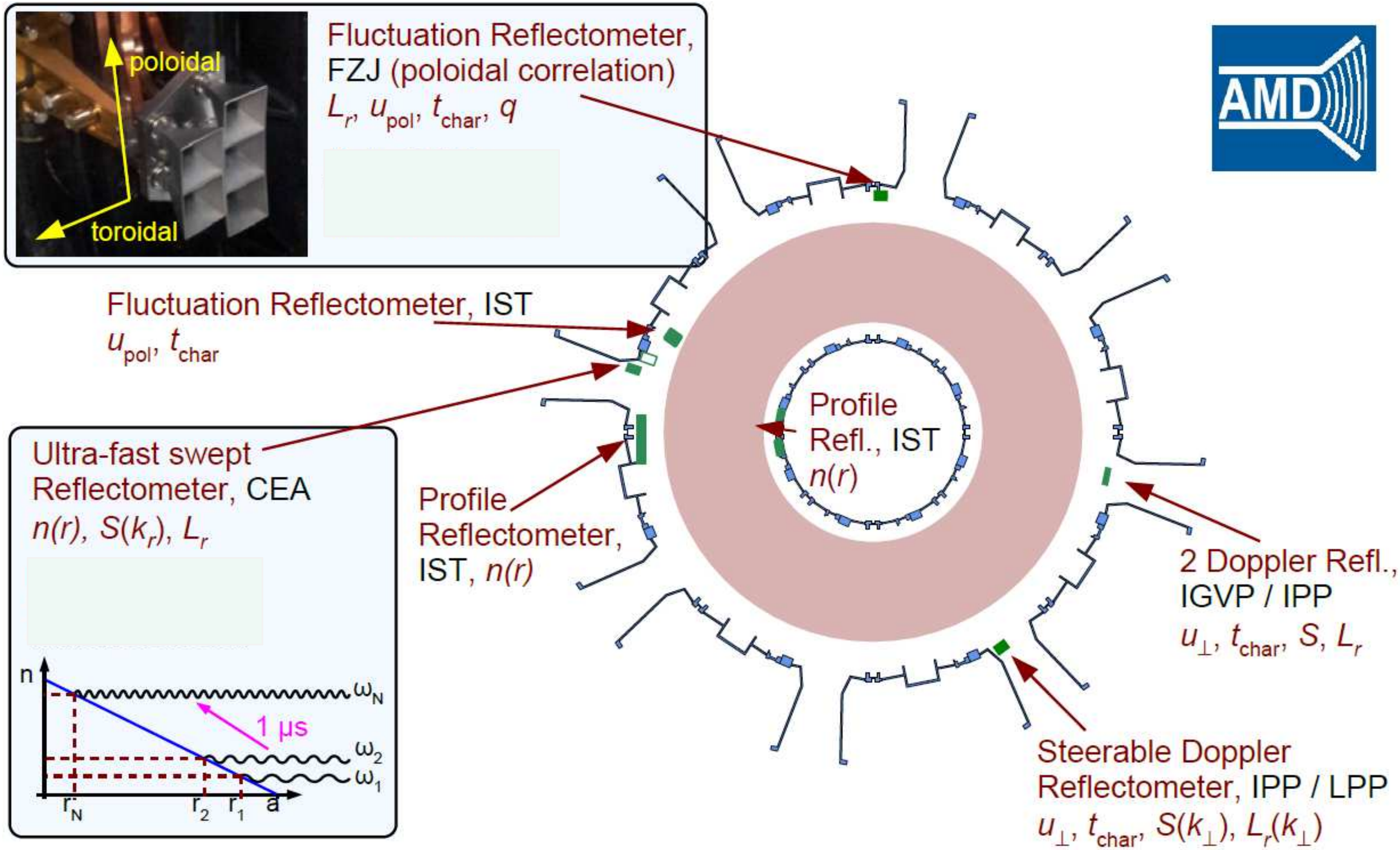
- ELMs still separate events, but much higher frequency, smaller ΔW
- due to strong density pumpout and $T_{i,ped}$ decrease, H is reduced
- optimum mitigation when field is peeling resonant (MARS-F analysis)

A. Kirk et al., this conference

Outline

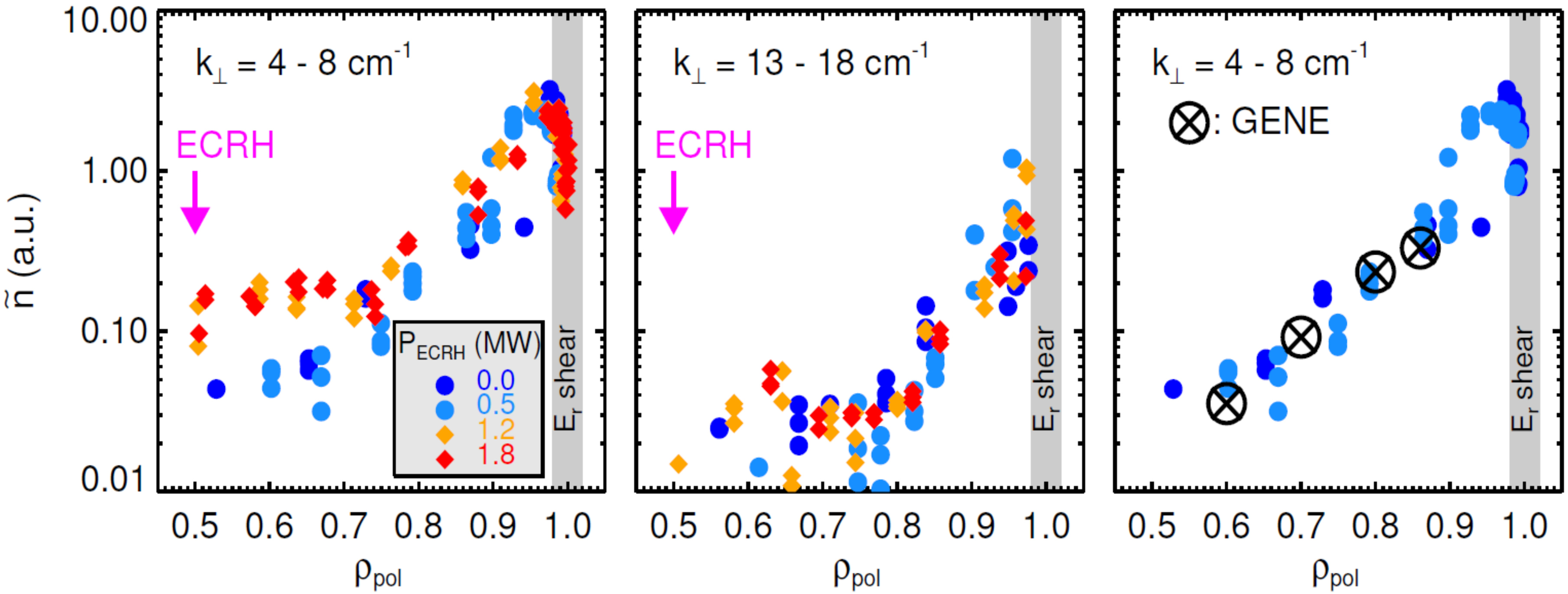
- ASDEX Upgrade: machine and programme
- Edge: H-mode access and pedestal physics
- Core: transport and MHD stability
- Exhaust: operation at high P_{sep}/R and $P_{rad,core}/P_{tot}$
- Scenario development

New Microwave Diagnostics for Turbulence Studies



U. Stroth et al,, this conference

Core transport: turbulence spectra during ECRH

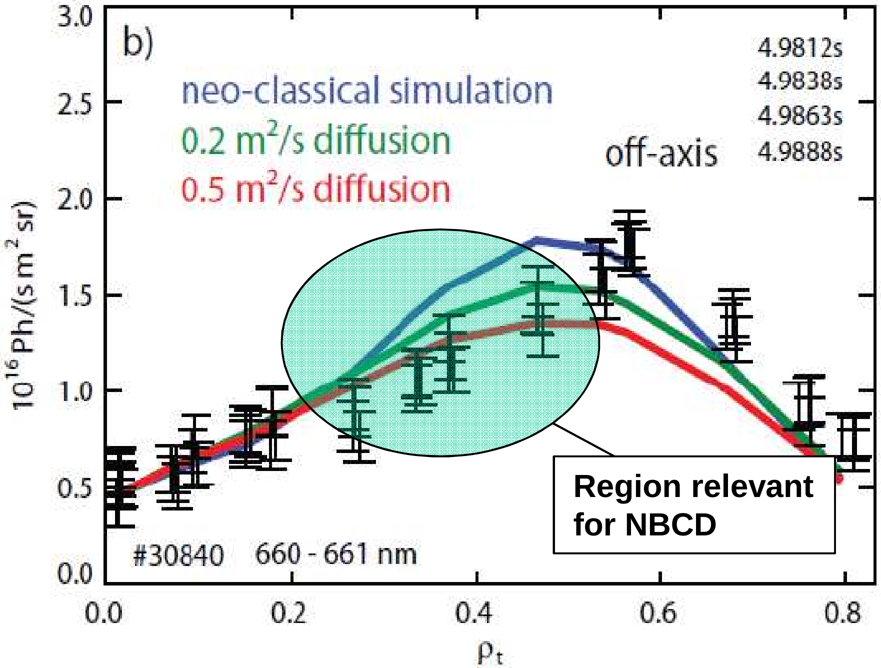


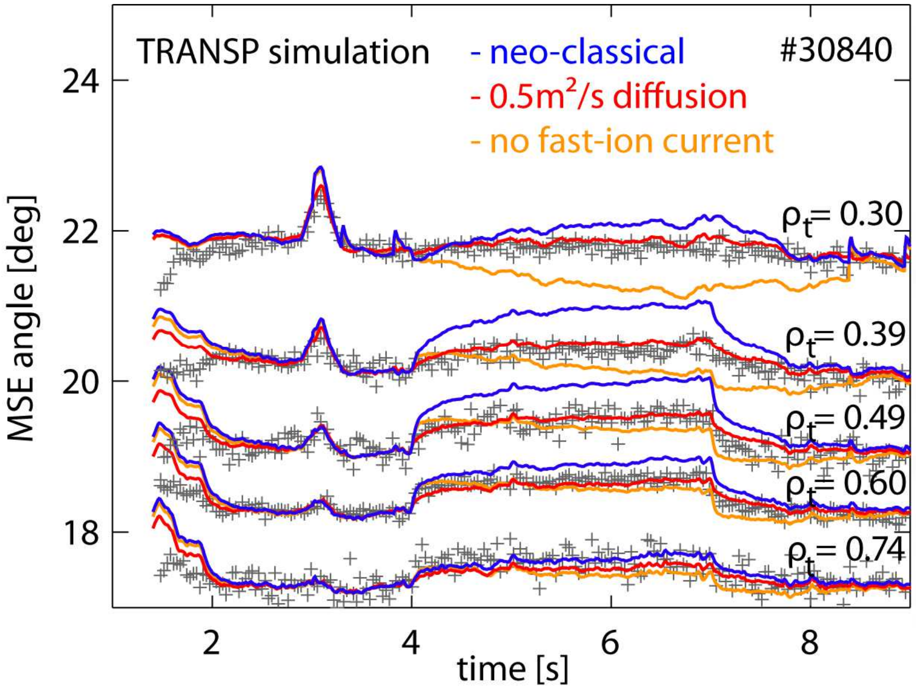
Response of density fluctuations to mid-radius ECRH in H-mode

- low ($k_\perp \approx$ 4-8 cm^{-1}) fluctuations increase while high $k_\perp$ does not
- radial amplitude dependence consistent with local flux matched nonlinear GENE simulations that find ITG-regime

T. Happel et al., subm. to Phys. Plasmas

Core transport: Fast Ions and NBCD



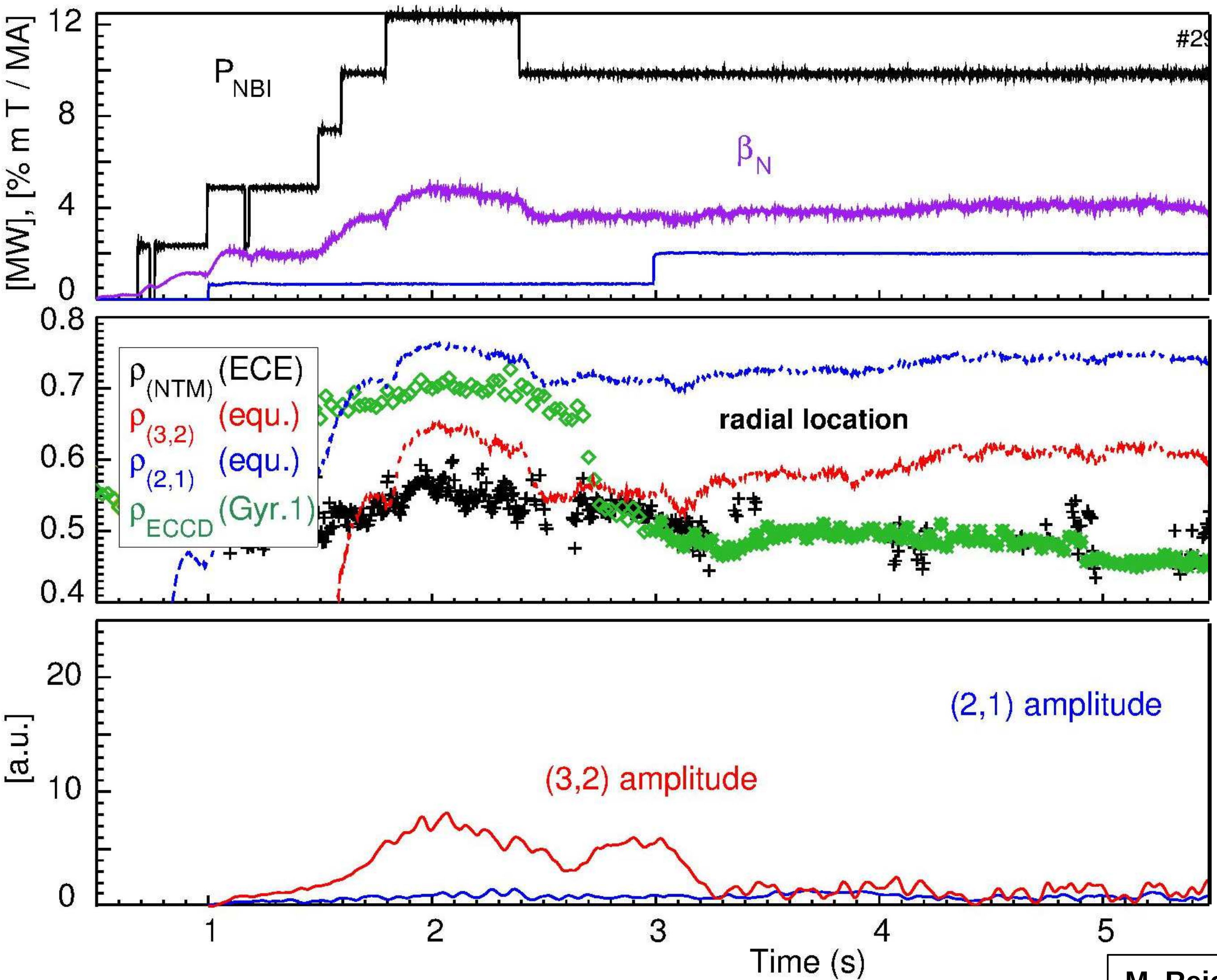


FIDA finds deviation from neo-classical slowing down at high P_{NBI}

- here, also NBCD not consistent with neo-classical prediction
- previous analysis indicated neo-classical slowing down at lower P_{NBI}
- cause not yet clearly identified (some MHD activity present)

B. Geiger et al., EPS 2014, to appear in PPCF

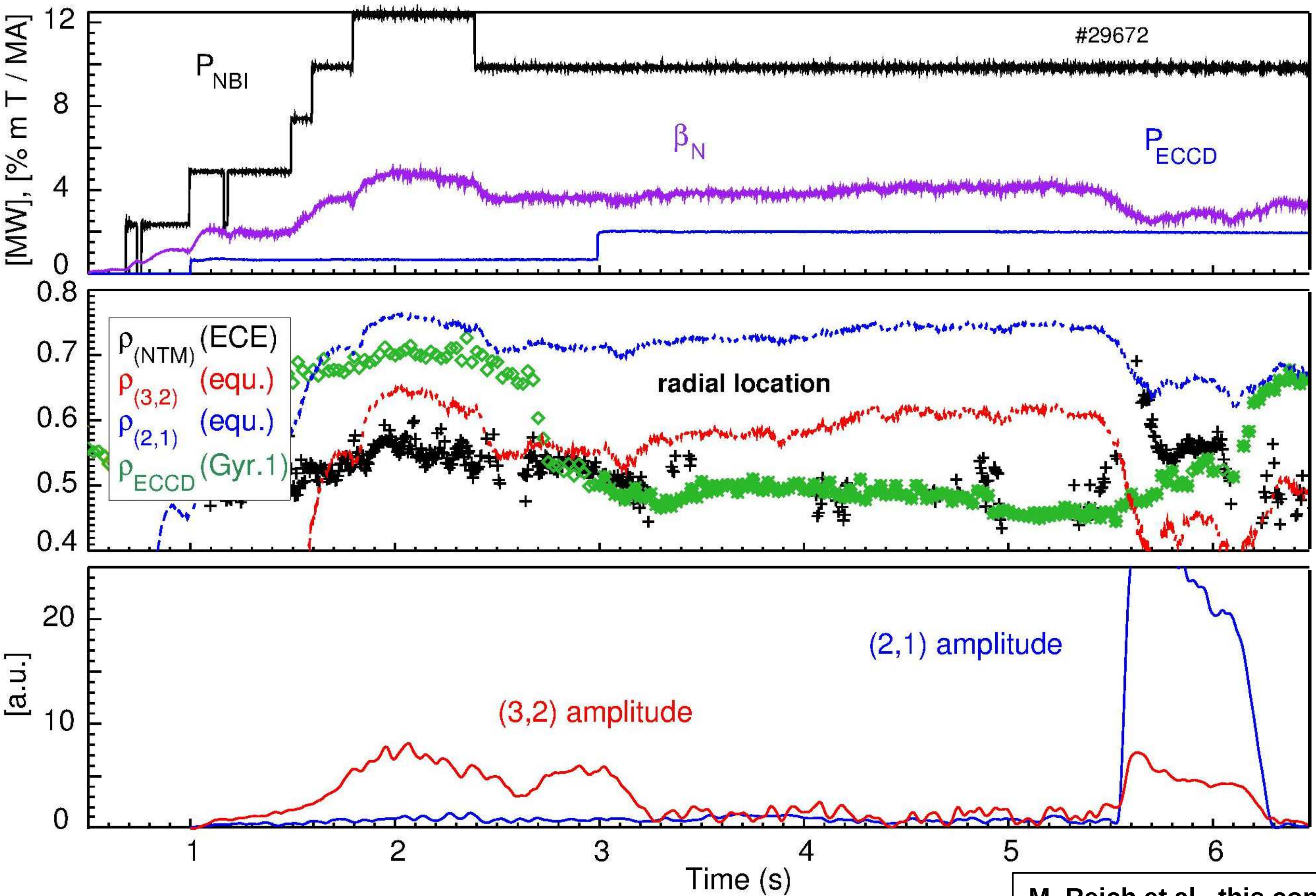
Core stability: NTM suppression by ECCD



M. Reich et al., this conference

Feedback system targets multiple mode control

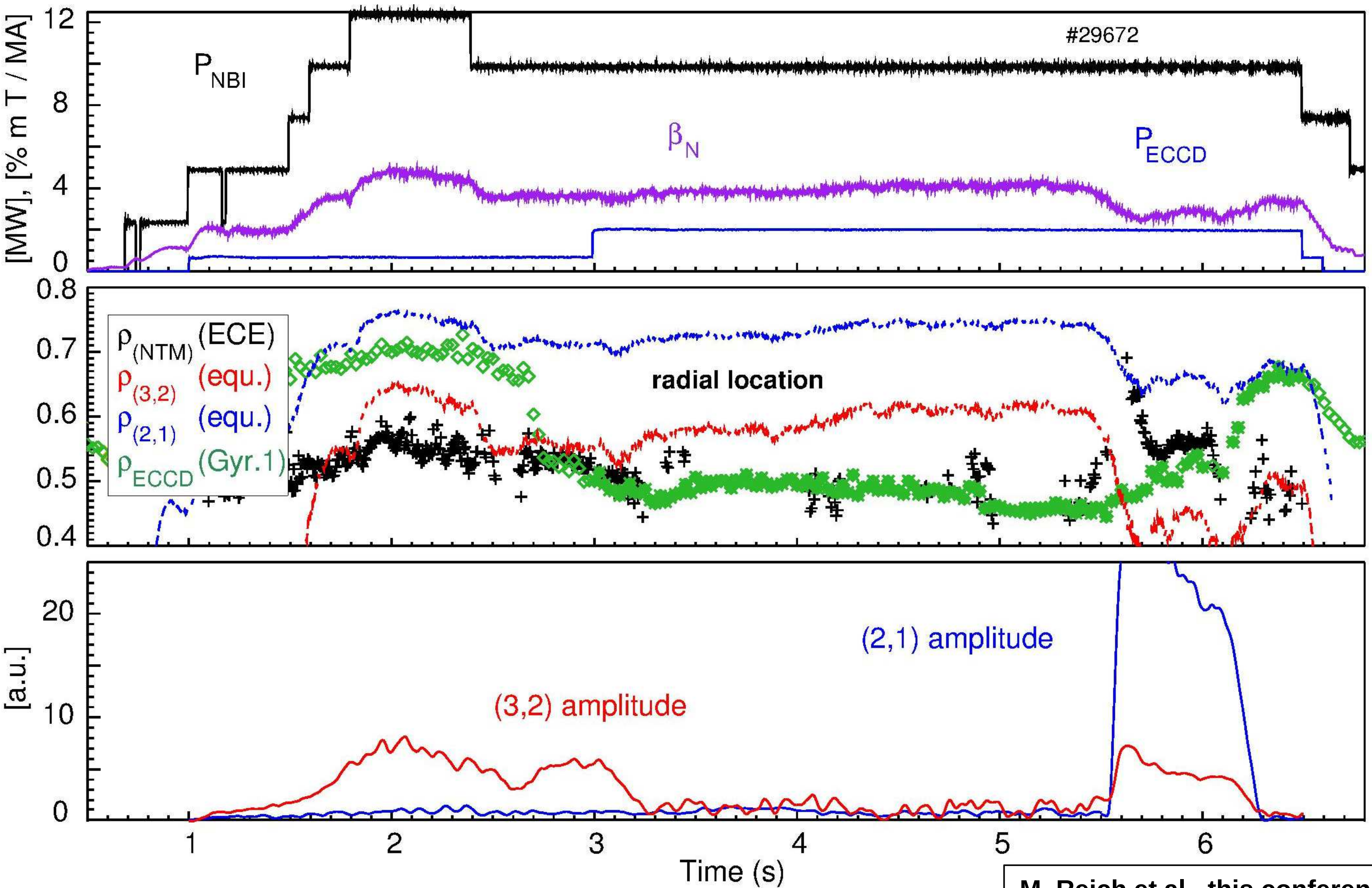
Core stability: NTM suppression by ECCD



M. Reich et al., this conference

Feedback system targets multiple mode control

Core stability: NTM suppression by ECCD



M. Reich et al., this conference

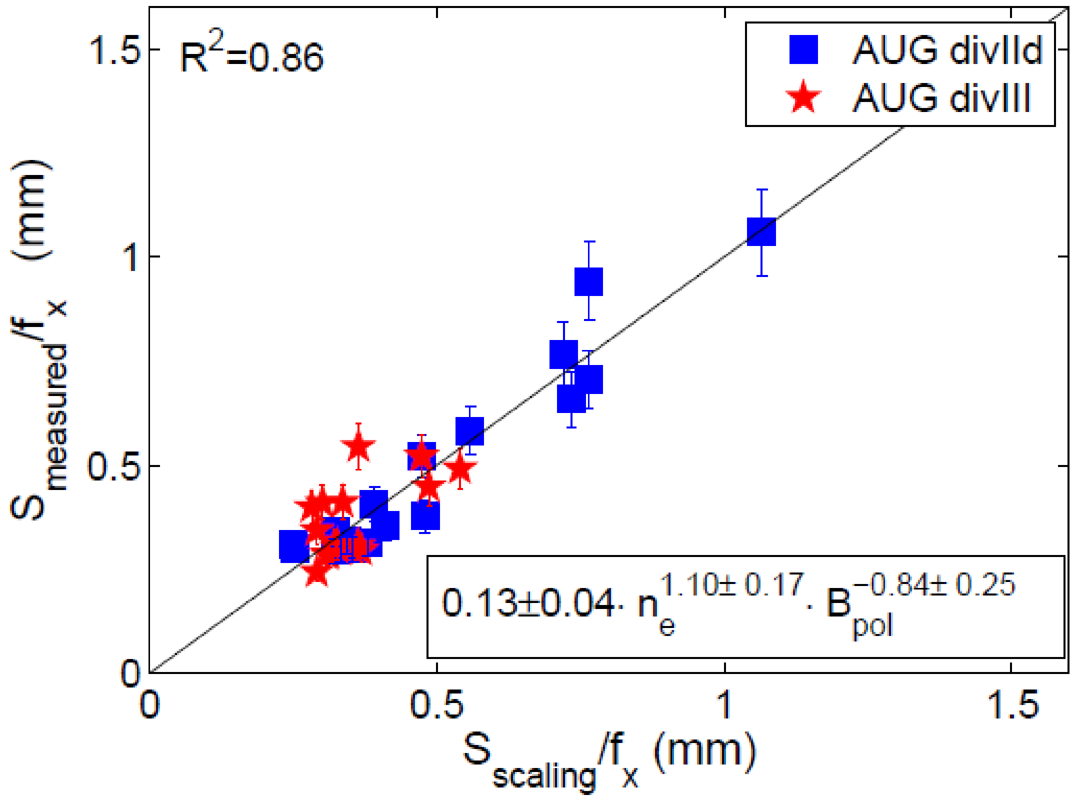
Feedback system targets multiple mode control

Outline

- ASDEX Upgrade: machine and programme
- Edge: H-mode access and pedestal physics
- Core: transport and MHD stability
- Exhaust: operation at high P_{sep}/R and $P_{rad,core}/P_{tot}$
- Scenario development

Broadening of divertor footprint

A. Scarabosio et al., PSI 2014
B.Sieglin et al., PPCF 2013



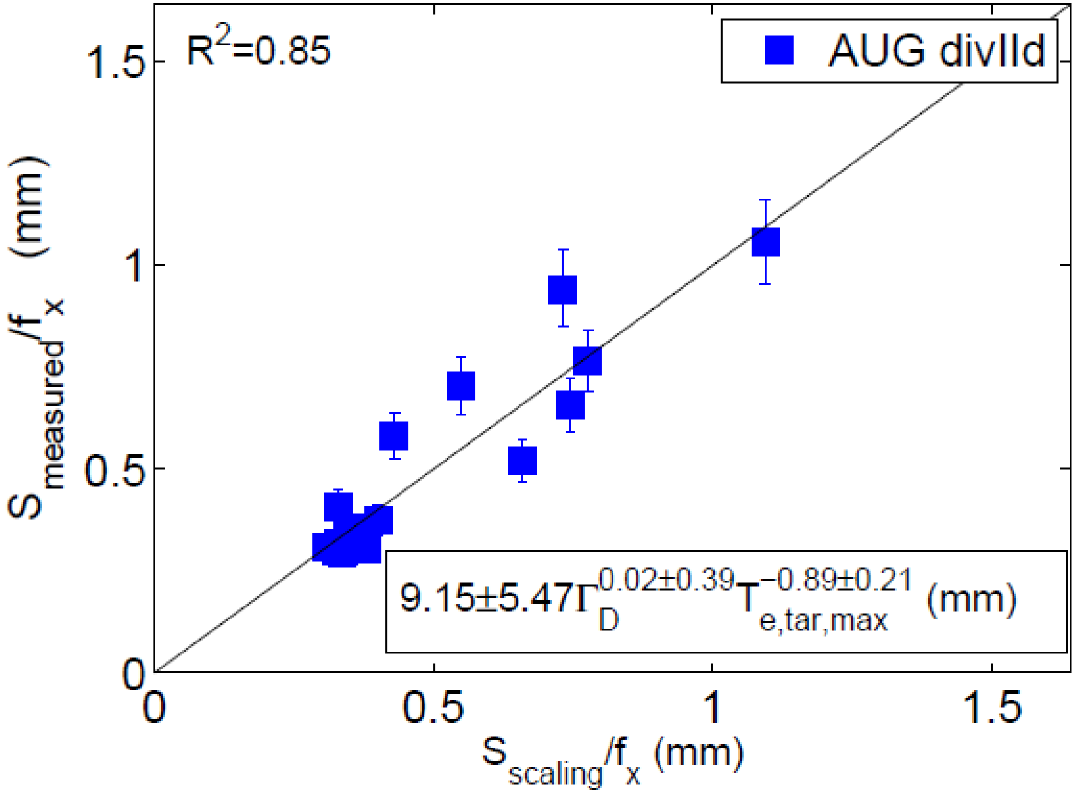
Midplane λ_q small, scales like ρ_p, not with R $\rightarrow$ figure of merit P_{sep}/R

- broadening by perpendicular transport described by $\lambda_{int} = \lambda_q + 1.64\ S$
- scaling: $S \sim n/B_p$ or $1/T_{target}$ – consistent with increased $\chi_{\perp}/\chi_{||}$

Emphasizes need for detached divertor operation in ITER/DEMO

Broadening of divertor footprint

A. Scarabosio et al., PSI 2014
B.Sieglin et al., PPCF 2013

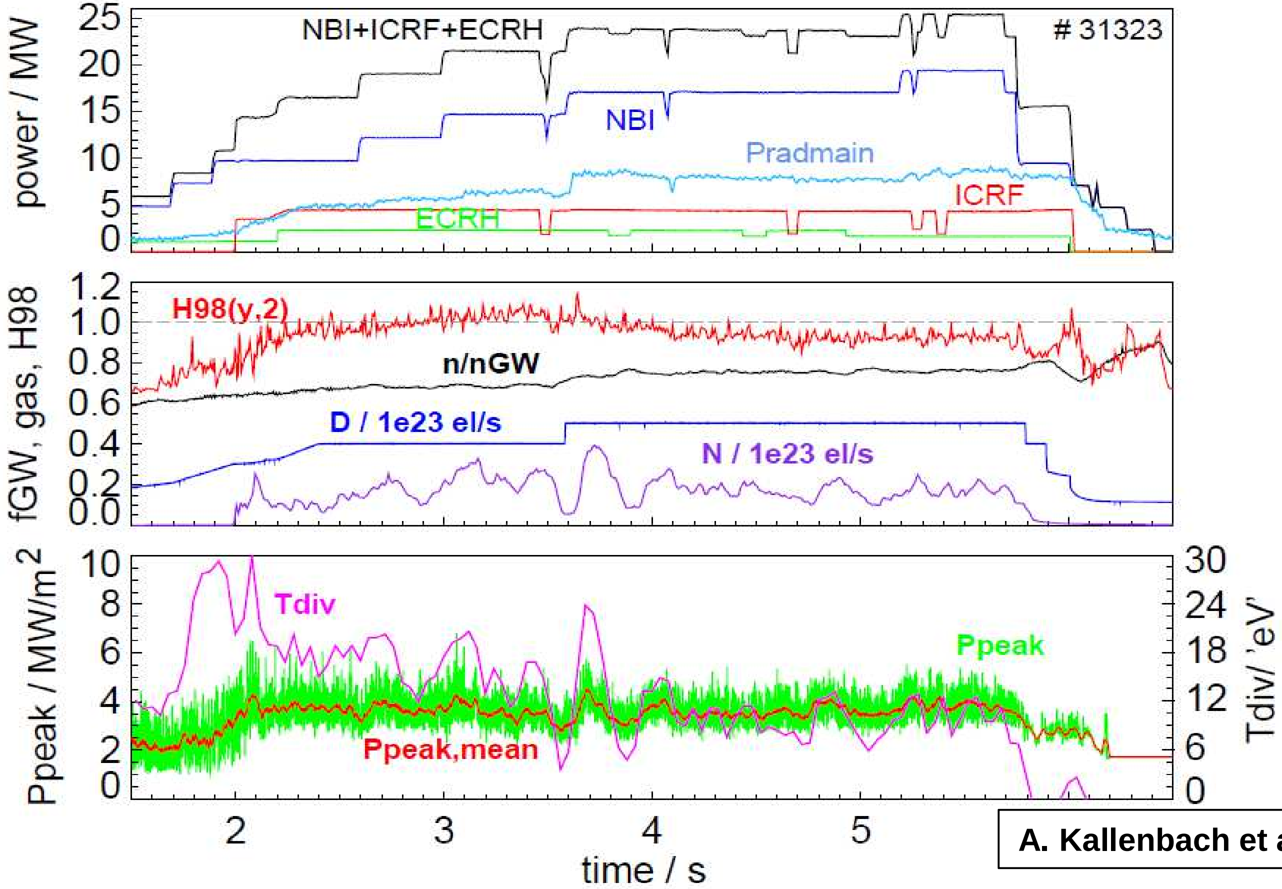


Midplane λ_q small, scales like ρ_p, not with R → figure of merit P_{sep}/R

- broadening by perpendicular transport described by $\lambda_{int} = \lambda_q + 1.64\ S$
- scaling: $S \sim n/B_p$ or $1/T_{target}$ – consistent with increased $\chi_\perp/\chi_\parallel$

Emphasizes need for detached divertor operation in ITER/DEMO

Partial detachment at high P_{sep}/R

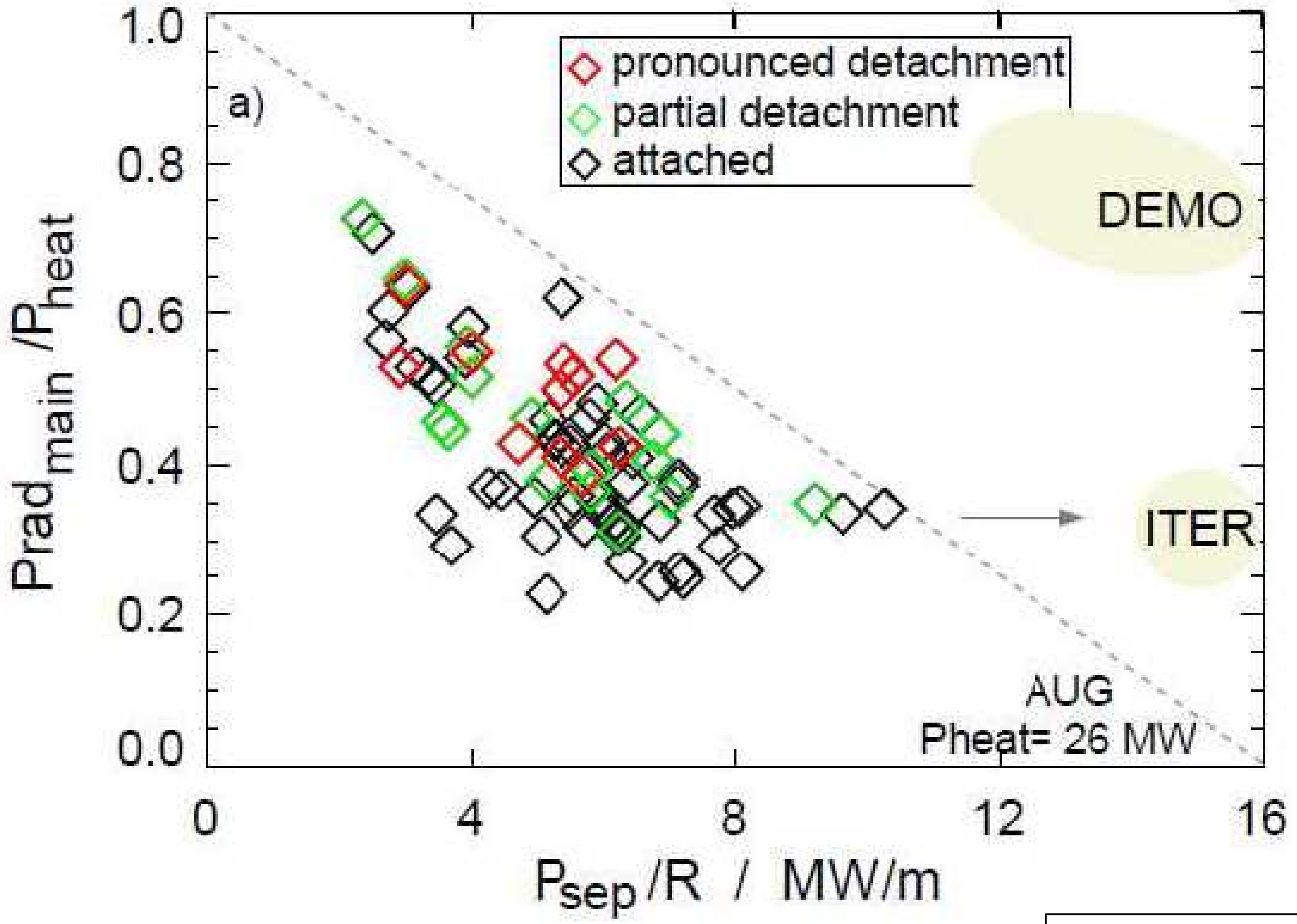


A. Kallenbach et al., this conference

Feedback controlled N-seeding: $q_{div} < 5$ MW/m^2 at $P_{heat} = 23$ MW

- P_{sep}/R = 10 MW/m (2/3 the ITER target) at H=0.9-1.0
- with higher stronger seeding, full detachment, but density rises, H drops

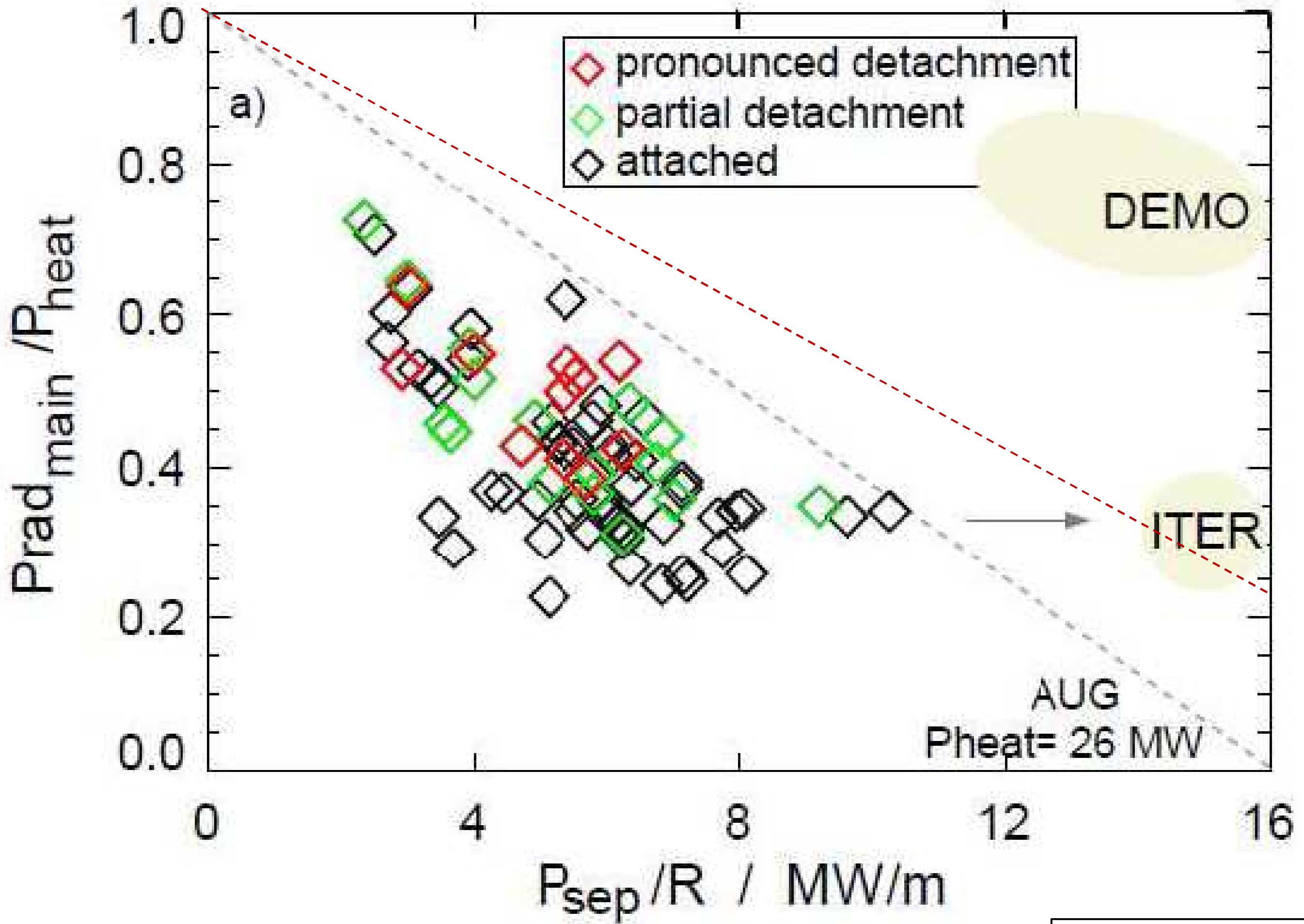
Exhaust: present and future capabilities



A. Kallenbach et al., this conference

Applying the ITER divertor solution to DEMO, high f_{rad} is needed

Exhaust: present and future capabilities



AUG with P_{heat}=34 MW

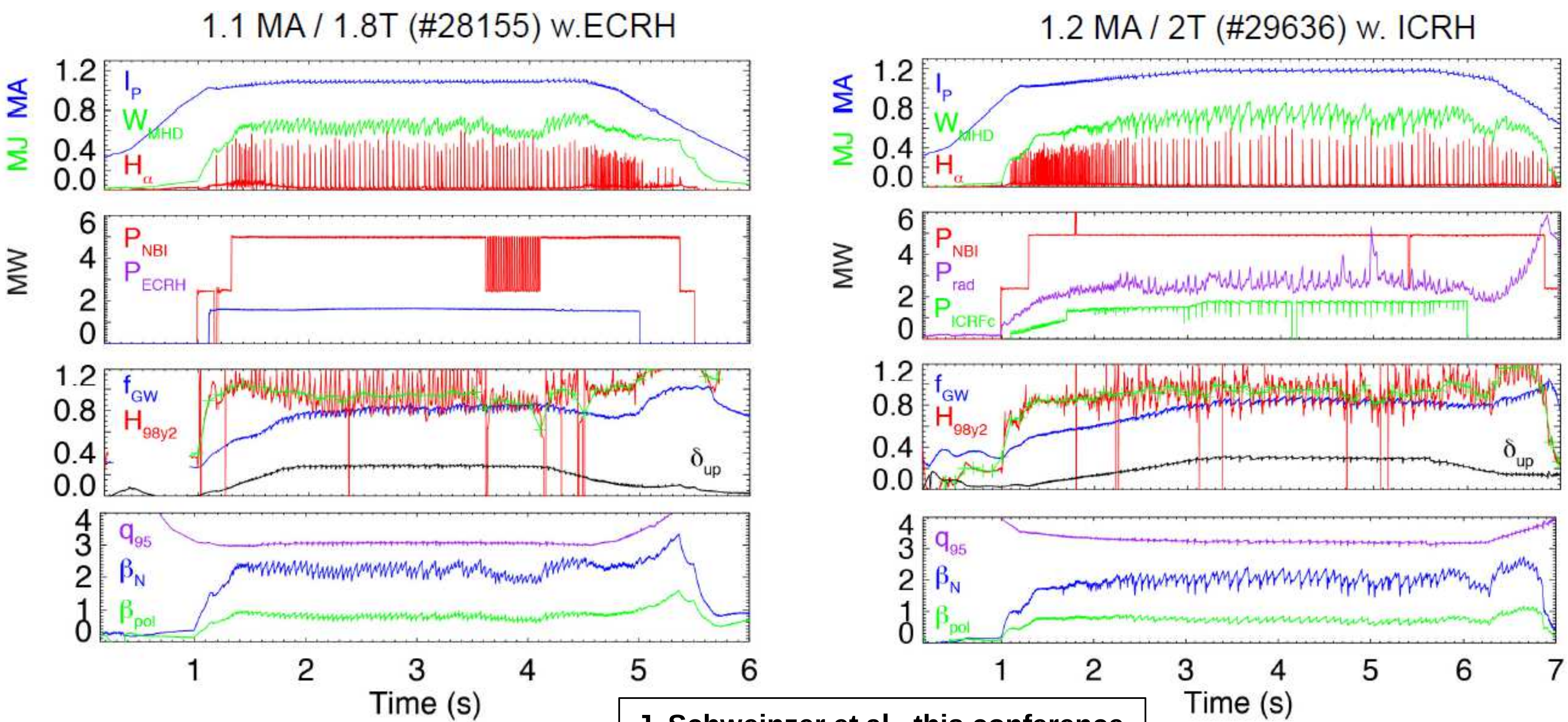
A. Kallenbach et al., this conference

Applying the ITER divertor solution to DEMO, high f_{rad} is needed

Outline

- ASDEX Upgrade: machine and programme
- Edge: H-mode access and pedestal physics
- Core: transport and MHD stability
- Exhaust: operation at high P_{sep}/R and $P_{rad,core}/P_{tot}$
- Scenario development

ITER baseline scenario development



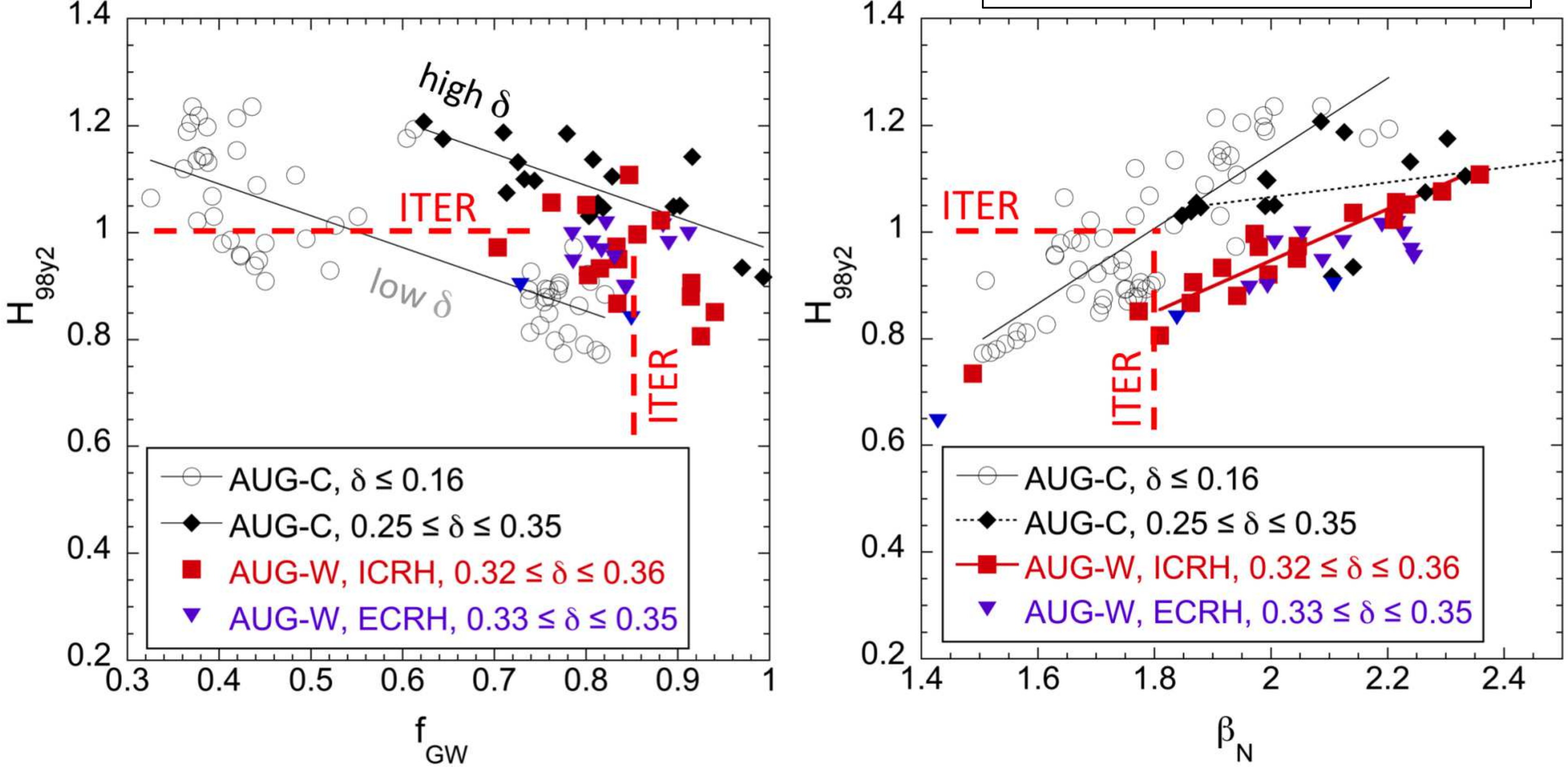
J. Schweinzer et al., this conference

Stable discharges as long as enough gas puff and central heating

- match is in q_{95}, δ, β_N, n/n_{GW}, and hence not in ν^* (also not in ρ^*)
- confinement reduced, H=0.85 at ITER β_N
- ELMs are large and mitigation techniques do not work reliably

ITER baseline scenario development

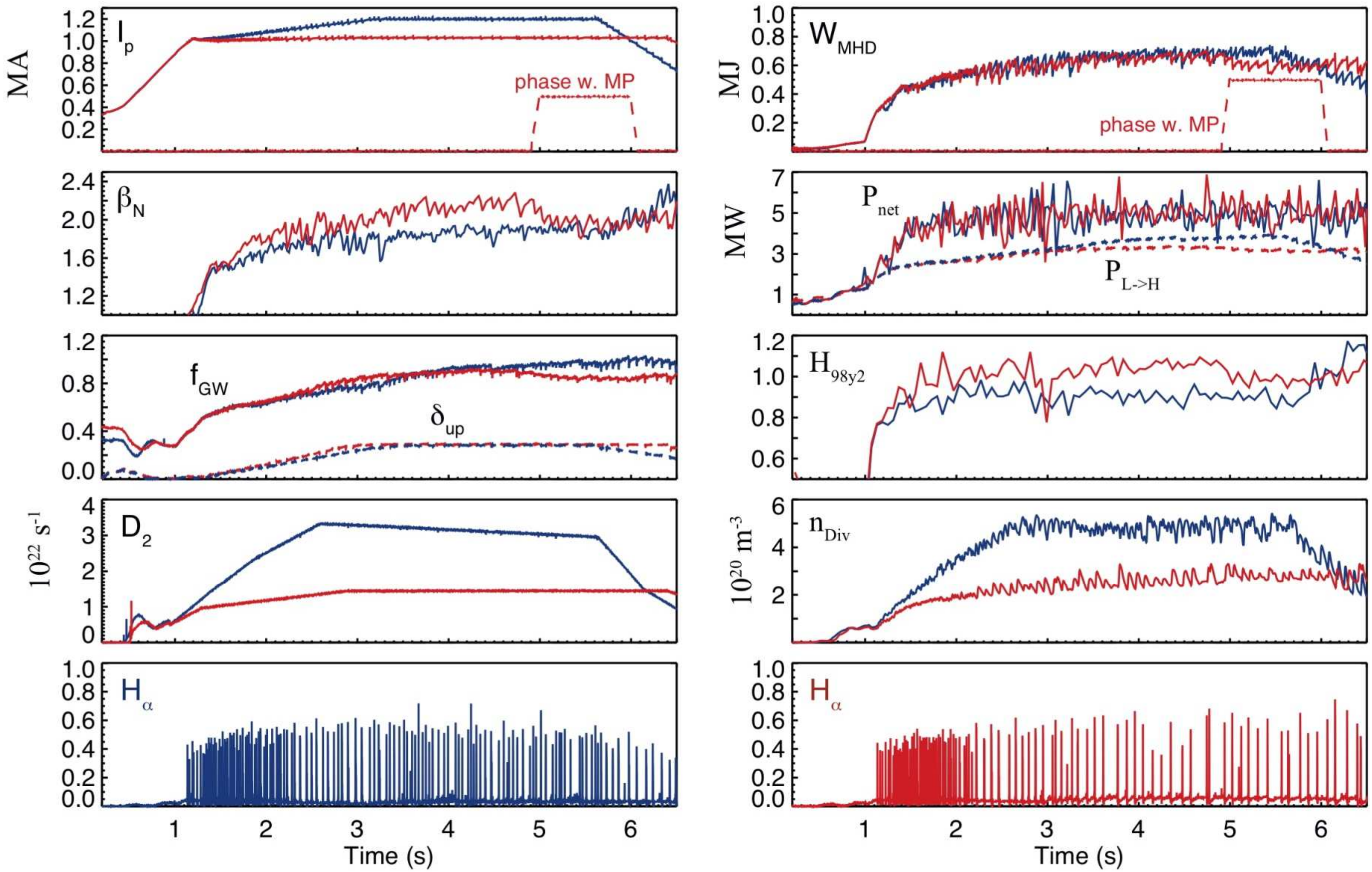
J. Schweinzer et al., this conference



Due to changed operational window, target can only be met at higher β_N

- gas puff needed to keep discharge stable, degrades pedestal
- with higher β_N and N-seeding H=1 is recovered (increased edge stability)

ITER baseline scenario development



These findings suggest to move to lower I_p, higher β_N ('improved H-mode')

- first attempt shows same W_{MHD} at 20% lower I_p, target for optimisation

The ASDEX Upgrade / EUROfusion MST1 Team

J. Ahn[1], L. Aho-Mantila[2], S. Äkäslompolo[2], C. Angioni, O. Asunta[2], M. de Baar[3], M. Balden, L. Barrera Orte, K. Behler, J. Belapure, A. Bergmann, J. Bernardo[4], M. Bernert, M. Beurskens[5], R. Bilato, G. Birkenmeier, V. Bobkov, A. Bock, A. Bogomolov[3], T. Bolzonella[6], J. Boom, B. Böswirth, C. Bottereau[1], A. Bottino, F. Braun, S. Brezinsek[7], F. Brochard[8], A. Buhler, A. Burckhart, P. Carvalho[4], C. Cazzaniga[6], D. Carralero, L. Casali, M. Cavedon, A. Chankin, I. Chapman[5], F. Clairet[1], I. Classen[3], S. Coda[9], R. Coelho[4], K. Coenen[7], L. Colas[1], G. Conway, S. Costea[10], D.P. Coster, G. Croci[11], G. Cseh[12], A. Czarnecka[13], P. de Marné, P. Denner[7], R. D'Inca, D. Douai[1], R. Drube, M. Dunne, B. Duval[9], R. Dux, T. Eich, S. Elgeti, K. Engelhardt, K. Ertl, B. Esposito[6], E. Fable, U. Fantz, H. Faugel, F. Felici[14], S. Fietz, A. Figueredo[4], R. Fischer, O. Ford, P. Franzen, L. Frassinetti[15], M. Fröschle, G. Fuchert[16], H. Fünfgelder, J.C. Fuchs, K. Gál-Hobirk, M. Garcia-Muñoz[17], B. Geiger, L. Giannone, E. Giovannozzi[6], C. Gleason-Gonzáles[7], T. Görler, T. Goodmann[9], G. Gorini[11], S. da Graca[4], A. Gräter, G. Granucci[11], H. Greuner, J. Grießhammer, M. Groth[2], A. Gude, S. Günter, L. Guimarais[4], G. Haas, A.H. Hakola[18], T. Happel, D. Hatch, T. Hauff, B. Heinemann, S. Heinzel, P. Hennequin[1], A. Herrmann, J. Hobirk, M. Hölzl, T. Höschen, J.H. Holm[19], C. Hopf, F. Hoppe, A. Houben, V. Igochine, T. Ilkei[11], W. Jacob, A.S. Jacobsen[19], J. Jacquot, M. Janzer, F. Jenko, T. Jensen[19], C. Käsemann, A. Kallenbach, S. Kálvin[12], M. Kantor[7], A. Kappatou[3], O. Kardaun, J. Karhunen[2], S. Kimmig, A. Kirk[5], H.-J.Klingshirn, M. Kocan, F. Koch, G. Kocsis[12], A. Köhn[16], M. Köppen, J. Kötterl, R. Koslowski[7], M. Koubiti[1], M. Kraus, K. Krieger, A. Krivska[20], D. Kogut[1], A. Krämer-Flecken[7], T. Kurki-Suonio[2], B. Kurzan, K. Lackner, F. Laggner[21], P.T. Lang, P. Lauber, N. Lazányi[12], A. Lazaros[22], A. Lebschy, F. Leuterer, Y. Liang[7], Ch. Linsmeier, A. Litnovski[7], A. Lohs, N.C. Luhmann[23], T. Lunt, H. Maier, O. Maj, J. Mailloux[5], A. Mancini[11], A. Manhard, K. Mank, M.-E. Manso[4], M. Mantsinen[24], P. Manz, M. Maraschek, E. Markina, C. Martens, P. Martin[25], A. Mayer, M. Mayer, D. Mazon[1], P.J. McCarthy[26], R. McDermott, G. Meisl, H. Meister, A. Medvedeva, P. Merkel, R. Merkel, V. Mertens, H. Meyer[5], O. Meyer[1], D. Milanesio[6], J. Miettunen[2], A. Mlynek, F. Monaco, D. Moseev, H.W. Müller, S. Müller[27], M. Münich, A. Nemes-Czopf[9], G. Neu, R. Neu, V. Nikolaeva[4], S.K. Nielsen[19], M. Nocente[11], B. Nold[16], J.-M. Noterdaeme, M. Oberkofler, R. Ochoukov, T. Odstrcil, G. Papp, H.K. Park[28], A. Pau[6], G. Pautasso, M.S. Pedersen[19], F. Penzel, P. Piovesan[25], C. Piron[25], B. Plaum[16], B. Plöckl, V. Plyusnin[4], Y. Podoba, G. Pokol[12], F. Pompon, E. Poli, K. Polozhiy, S. Potzel, R. Preuss, D. Prisiazhniuk, T. Pütterich, M. Ramish[16], C. Rapson, J. Rasmussen[19], S.K. Rathgeber, G. Raupp, D. Réfy[9], M. Reich, F. Reimold, M. Reinke[5], T. Ribeiro, R. Riedl, G. Rocchi[11], M. Rodriguez-Ramos[17], V. Rohde, J. Roth, M. Rott, F. Ryter, M. Salewski[19], L. Sanchis-Sanchez[17], G. Santos[4], J. Santos[4], P. Sauter, A. Scarabosio, G. Schall, K. Schmid, O. Schmitz[29], P.A. Schneider, W. Schneider, M. Schneller, R. Schrittwieser[10], M. Schubert, T. Schwarz-Selinger, J. Schweinzer, B. Scott, T. Sehmer, M. Sertoli, A. Shalpegin[30], G. Sias[6], M. Siccinio, B. Sieglin, A. Sigalov, A. Silva[4], C. Silva[4], P. Simon, F. Sommer, C. Sozzi[11], M. Spolaore[6], M. Stejner Petersen[19], J. Stober, F. Stobbe, U. Stroth, E. Strumberger, K. Sugiyama, H.-J. Sun, W. Suttrop, T. Szepesi[12], T. Tala[2], G. Tardini, C. Tichmann, D. Told, L. Tophøj[19], O. Tudisco[6], U. von Toussaint, G. Trevisan[25], W. Treutterer, M. Valovic[5], P. Varela[4], S. Varoutis[7], D. Vezinet, N. Vianello[25], J. Vicente[4], T. Vierle, E. Viezzer, C. Vorpahl, D. Wagner, X. Wang, T. Wauters[20], I. Weidl, M. Weiland, A. Weller, R. Wenninger, B. Wieland, M. Wiesinger[21], M.Willensdorfer, B. Wiringer, M. Wischmeier, R. Wolf, E. Wolfrum, D. Wünderlich, E. Würsching, Z. Yang, Q. Yu, I. Zammuto, D. Zarzoso, D. Zasche, M. van Zeeland[31], T. Zehetbauer, M. Zilker, S. Zoletnik[12], H. Zohm

Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany;
[2]Tekes, Aalto University, Helsinki, Finland;
[4]CFN, IST Lisbon, Portugal;
[6]C.R.E, ENEA Frascati, CP 65, 00044 Frascati (Rome), Italy;
[8]Institut Jean Lamour, UMR 7193 CNRS, Vandoeuvre, France;
[10]ÖÄW, University of Innsbruck, Austria;
[12]KFKI, HAS, Budapest, Hungary;
[14]Technische Universiteit Eindhoven, The Netherlands;
[16]IGVP, Universität Stuttgart, Germany;
[18]TEKES VTT, Espoo, Finland;
[20]ERM/KMS, Brussels, Belgium;
[22]Hellenic Republic, Athen, Greece;
[24]CIEMAT, Madrid, Spain;
[26]DCU, University College Cork, Ireland;
[28]Gwacheon, South Korea;
[30]University of Nancy, France;

[1]CEA, Cadarache, France;
[3]FOM-Institute DIFFER, TEC, Nieuwegein, The Netherlands;
[5]CCFE Fusion Association, Culham Science Centre, UK;
[7]Forschungszentrum Jülich, Germany;
[9]CRPP, Lausanne, Switzerland;
[11]ENEA, IFP, CNR, Milano, Italy;
[13]Warsaw University of Technology, 00-661 Warsaw, Poland;
[15]VR, Stockholm, Sweden;
[17]University of Seville, Spain;
[19]DTU, Kgs. Lyngby, Denmark;
[21]ÖAW, IAP, TU Wien, Austria;
[23]University of California, Davis, CA 95616, USA;
[25]Consorzio RFX, ENEA, Padova, Italy;
[27]University of California, San Diego, CA 92110, USA;
[29]University of Madison, Wisconsin, USA;