Overview of ASDEX Upgrade Results –
Development of integrated operating scenarios for ITER

The ASDEX Upgrade Team
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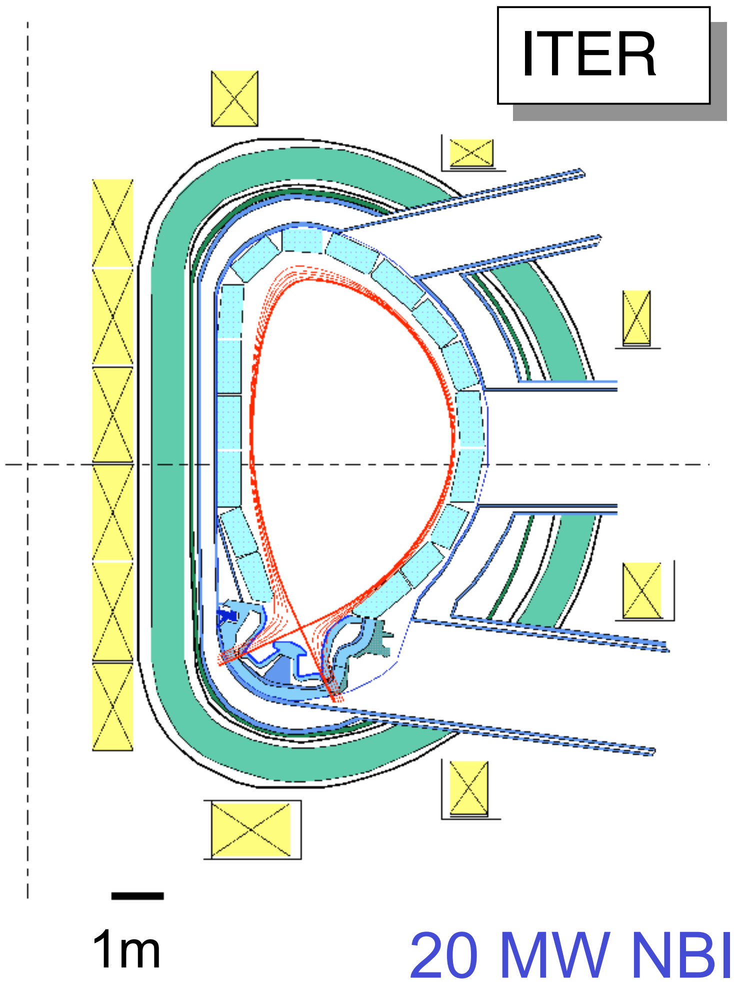
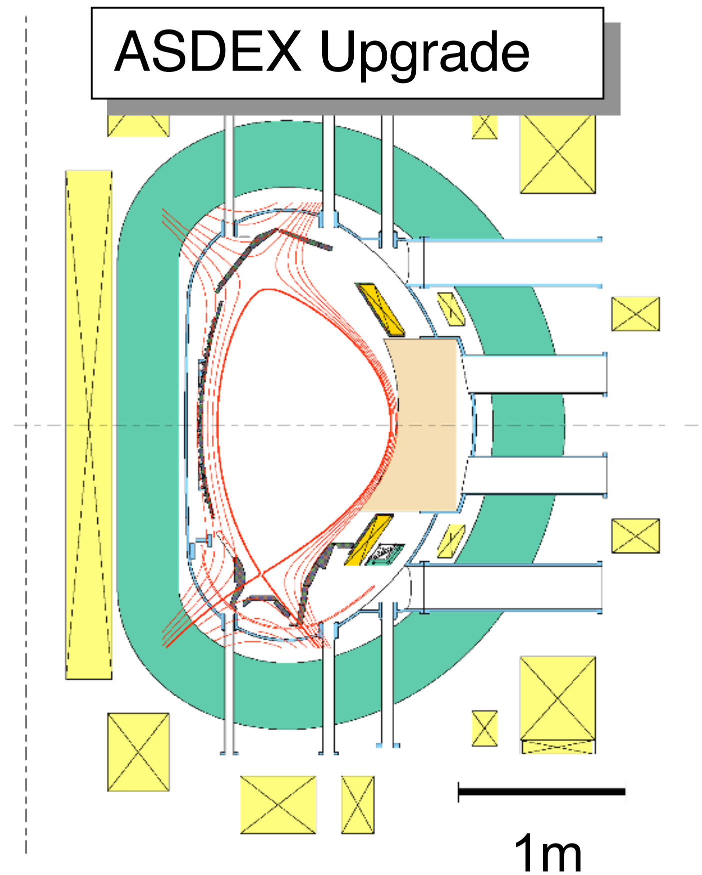
Many thanks to our collaborating institutes:

Institute of Atomic Physics, Romania; Consorzio RFX, Padova, Italy; Centro de Fusão Nuclear, IST Lisbon, Portugal; IFP Milano, Italy; University College Cork, Ireland; KFKI Research Institute, Budapest, Hungary; University Stuttgart, Germany; HUT Helsinki, Espoo, Finland; VTT Technical Research Centre, Espoo, Finland; Plasma Physics Laboratory, Brussels, Belgium; Demokritos, Institute of Nuclear Technology, Attiki, Greece; KTH-Alba Nora, University Stockholm, Sweden; UKAEA Culham, GB; CRPP Lausanne, Switzerland; PPPL Princeton, U.S.A.

ASDEX Upgrade programme focuses on ITER





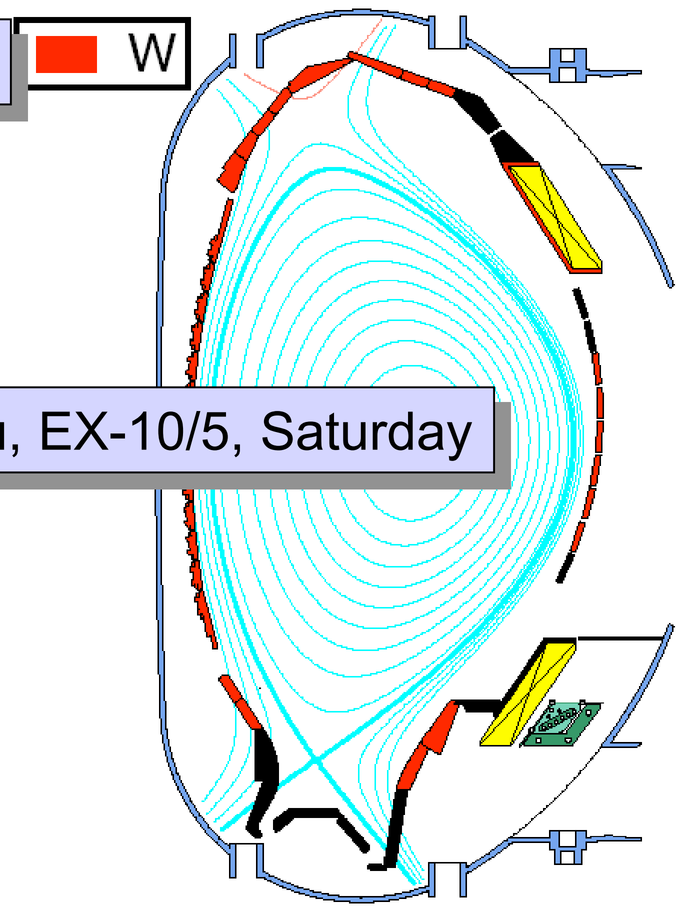
20 MW NBI (on- and off-axis)
< 8 MW ICRH
2 MW ECRH

ASDEX Upgrade programme focusses on ITER

Operation scenarios must be compatible with W as plasma facing material

With C long-term retention of D: 3.5% of input

See poster by M. Mayer, EX-P-5/24, Friday



Step by step towards a C free machine:

• 65 % of plasma facing components W coated

See talk by R. Neu, EX-10/5, Saturday

Further hardware upgrades:

• 10 s flat top (~ 5 current diffusion times)
• higher triangularity: δ=0.55 for $\kappa\leq$1.7 (includes ITER shape)
• diagnostic upgrades

- **Particle and energy transport**
- Pedestal physics and ELM control
- Plasma wall interaction and impurity transport
- Core MHD stability
- Current profile tailoring

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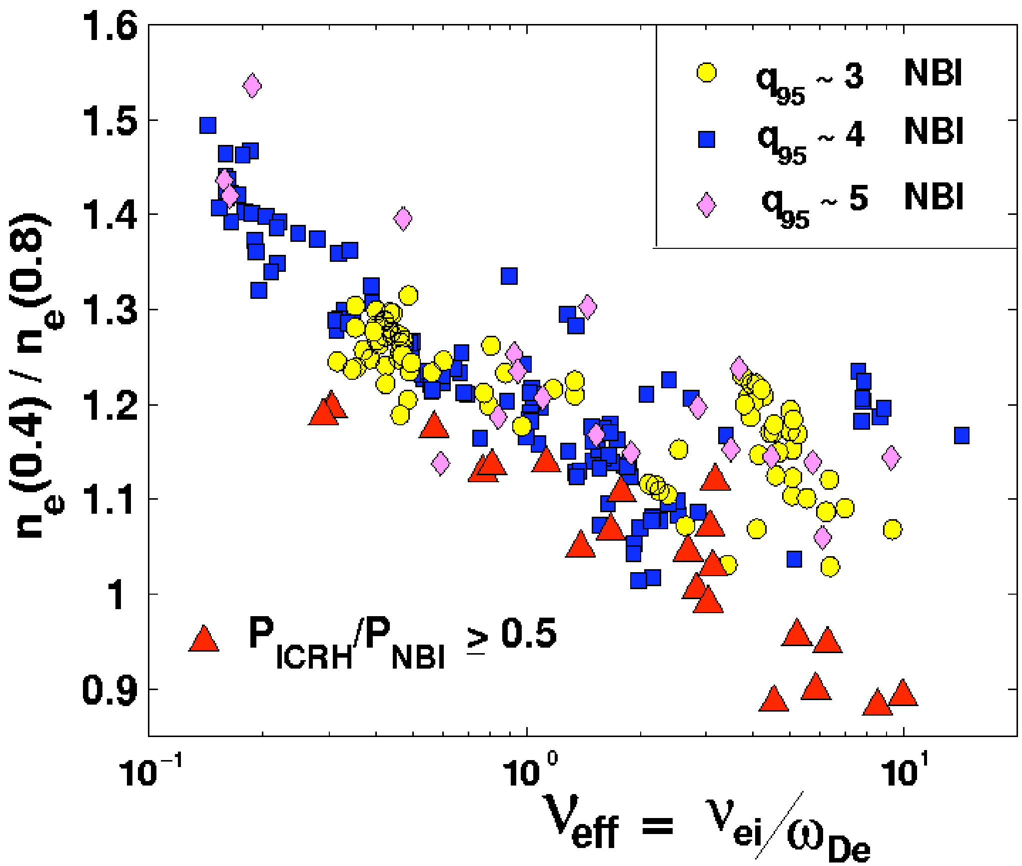
Integrated scenario

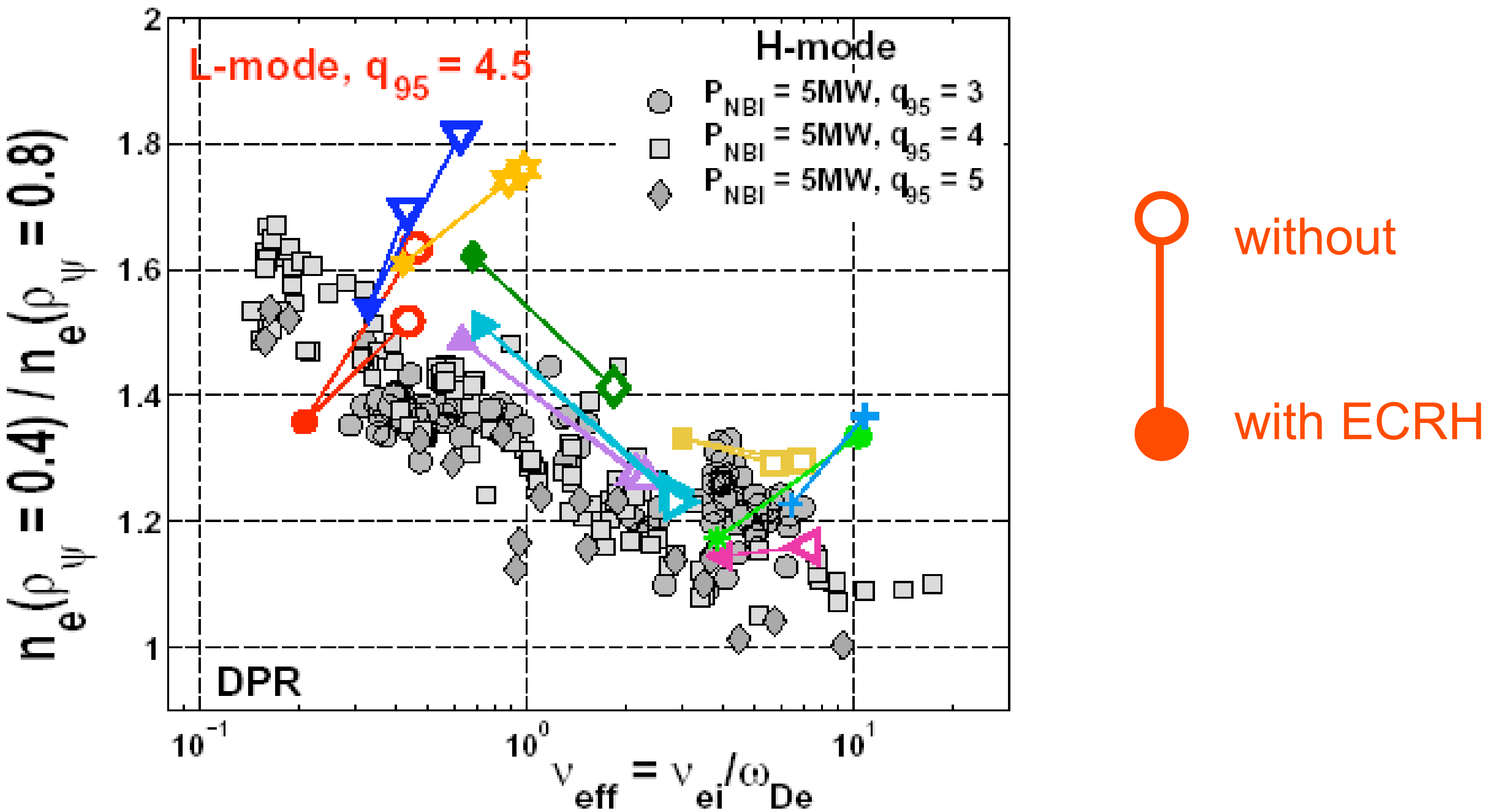
Collisionality dependence of particle transport



no strong central (electron) heating

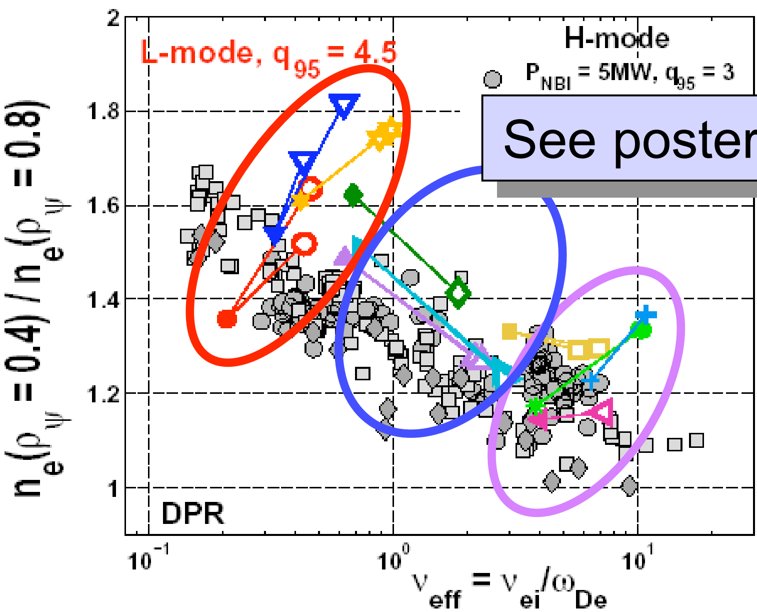
Density peaking increases with decreasing collisionality (H-mode and L-mode), consistent with quasi-linear ITG/TEM model

Reaction of the density profile to central electron heating



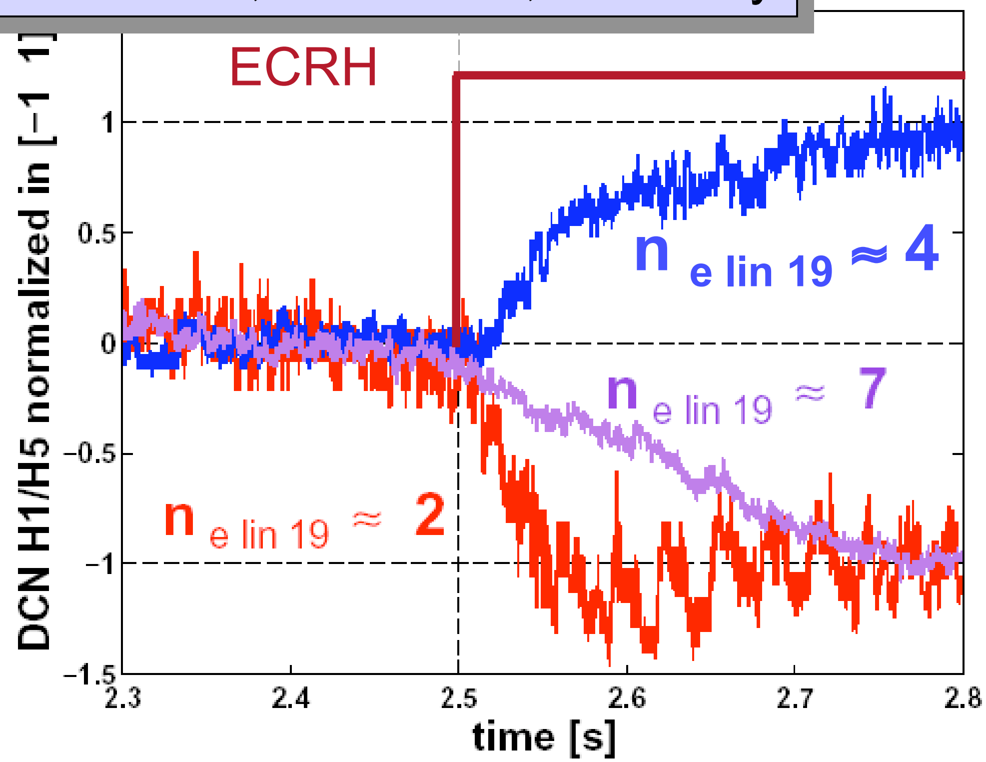
Reaction of density profiles and corresponding time scales again consistent with quasi-linear ITG/TEM model

Control of density profile by central electron heating



Decreased collisionality ⇒ increased anomalous inward pinch

See poster by A. Peeters, EX-P-3/10, Thursday



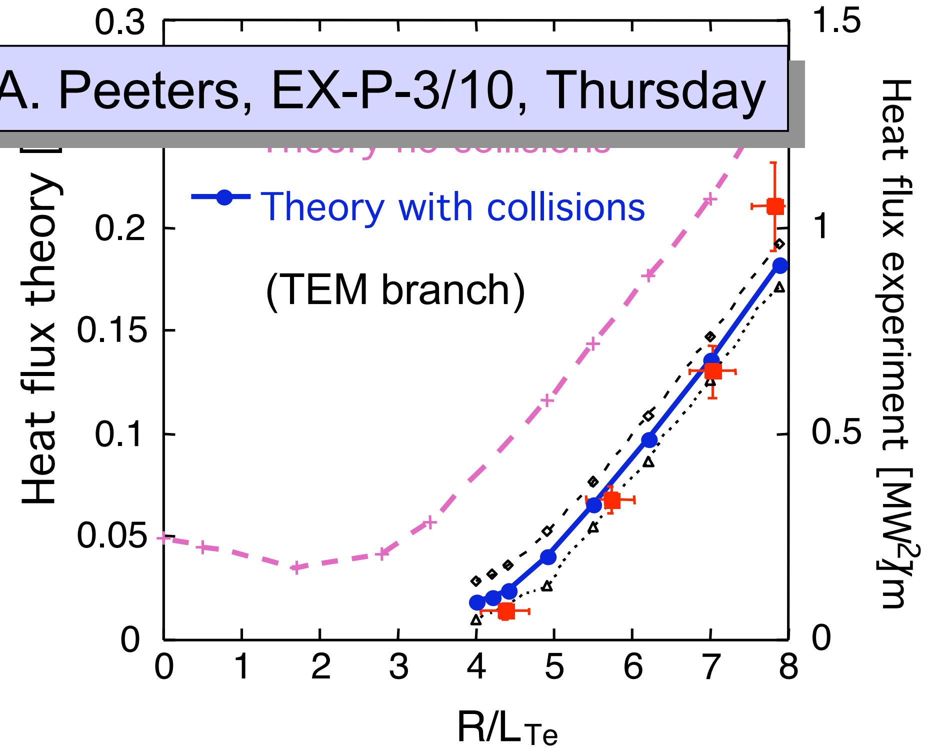
TEM induced thermodiffusion (counteracts anomalous inward pinch)

Increased thermodiffusion (D~χ) counteracts neoclassical Ware pinch

Electron heat transport in agreement with the ITG/TEM model

ECRH in Ohmic discharge:

- constant power
- heat deposition profile varied



See poster by A. Peeters, EX-P-3/10, Thursday

Good agreement with quasi-linear GS2 modelling

TEM most unstable ⇒ collisions and denstity gradient are important

See poster by A. Jacchia, EX-P-6/17, Friday

- Particle and energy transport
- **Pedestal physics and ELM control**
- Plasma wall interaction and impurity transport
- Core MHD stability
- Current profile tailoring

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Integrated scenario

Pedestal physics investigations with improved diagnostics

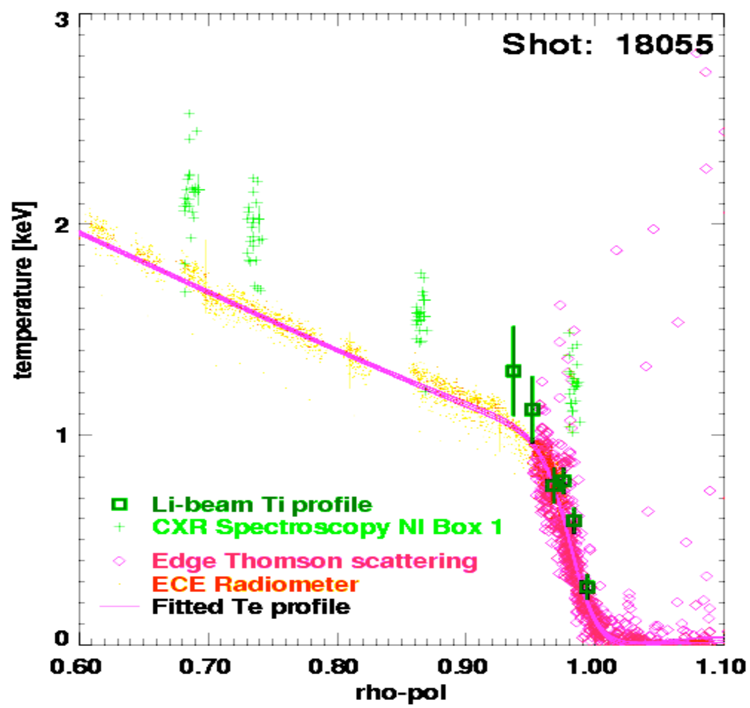
- Reflectometry for high temporal and spatial resolution density profile measurements (ELM e

See poster by I. Nunes, EX-P-6/20 Friday

- Li-beam CX for ion edge temperatures
- Upgrade of Thomson scattering system

(2.7 mm radial separation, 2 μs burst)

$T_{i,ped} \geq T_{e,ped}$

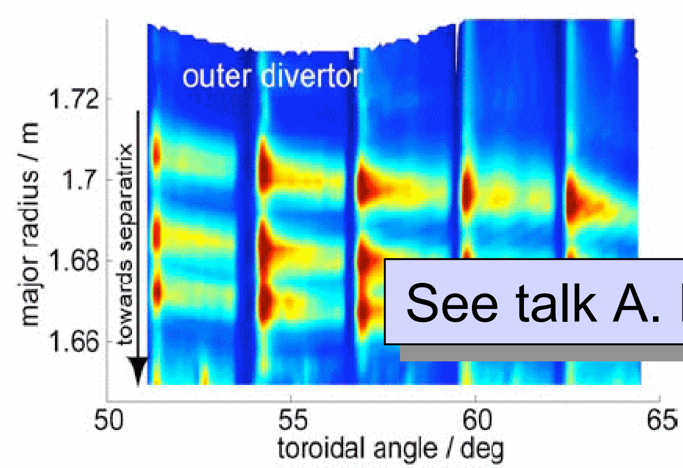


- d log T_e/d log n_e~ 2 confirmed
- toroidal mode numbers for ELMs: n~3-14

See poster by L. Horton, EX-P-3/4, Thursday

Pedestal physics investigations with improved diagnostics

- Fast framing IR camera for structure of heat deposition

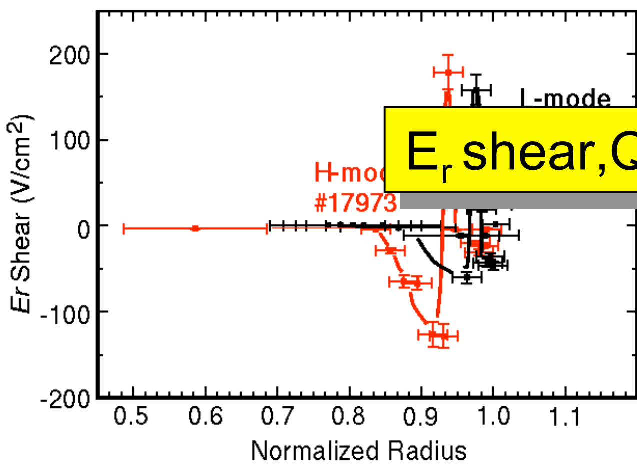


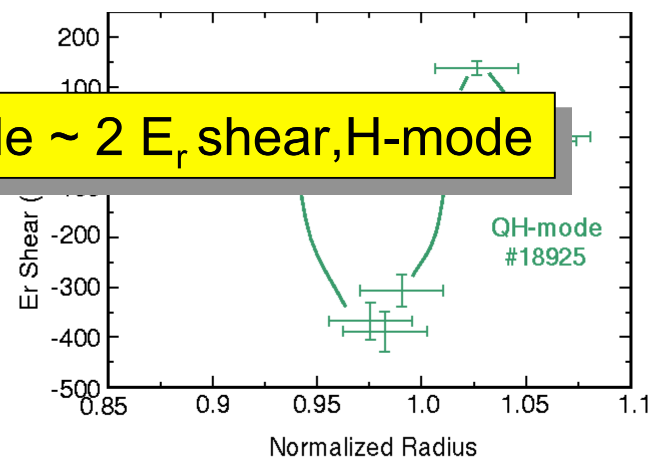
toroidal mode numbers for ELMs

n~ 3 … 15

See talk A. Herrmann, EX-2/4Rb, Tuesday

- Correlation Doppler reflectometry (E_r, E_r shear, correlation length)



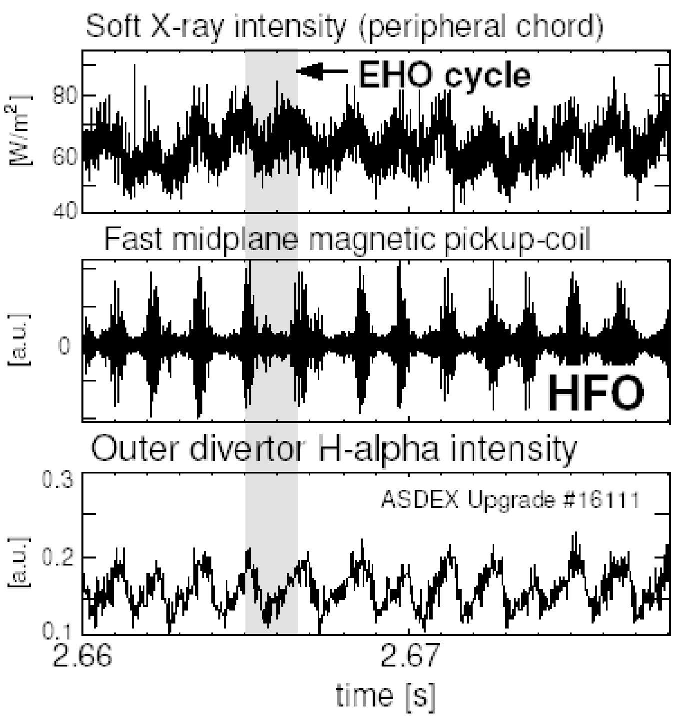


E_r shear,QH-mode ~ 2 E_r shear,H-mode

Quiescent H-mode: an ELM free scenario for ITER?

QH-mode:

- stationary, ELM free (at ITER υ^*)
- ELMs replaced by other MHD (EHO,HFO – fast particle driven?)
- **Z_{eff} down to 2.5**

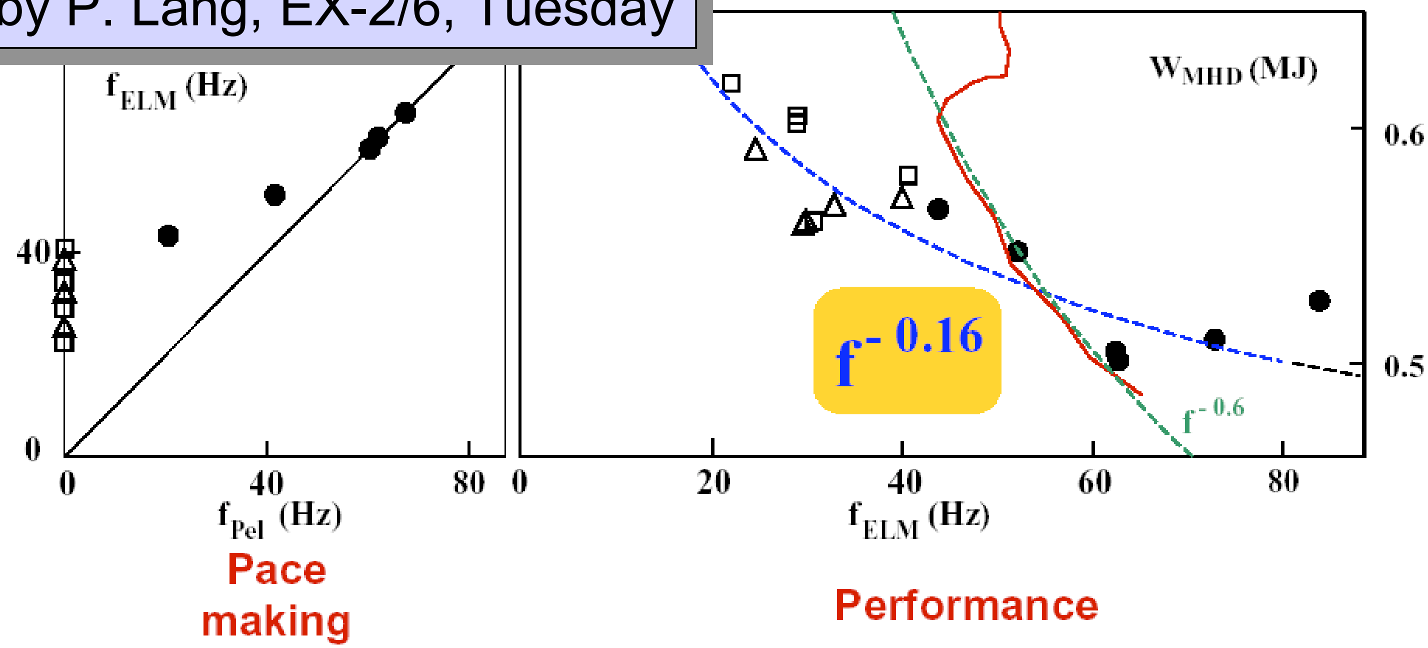


See talk by W. Suttrop, EX-1/4, Tuesday

ELM control by pellet pace making

Replace linearly unstable peeling/ballooning mode by local trigger perturbation

See talk by P. Lang, EX-2/6, Tuesday



- only minor confinement degradation with increased ELM frequency compared to, e.g., gas puffing (pedestal temperature reduced!)
- energy loss per ELM for pellet triggered ELMs as for “natural” ELMs
- successful ELM control also by small wobbling (as in TCV)

- Particle and energy transport
- Pedestal physics and ELM control
- Plasma wall interaction and impurity transport
- Core MHD stability
- Current profile tailoring

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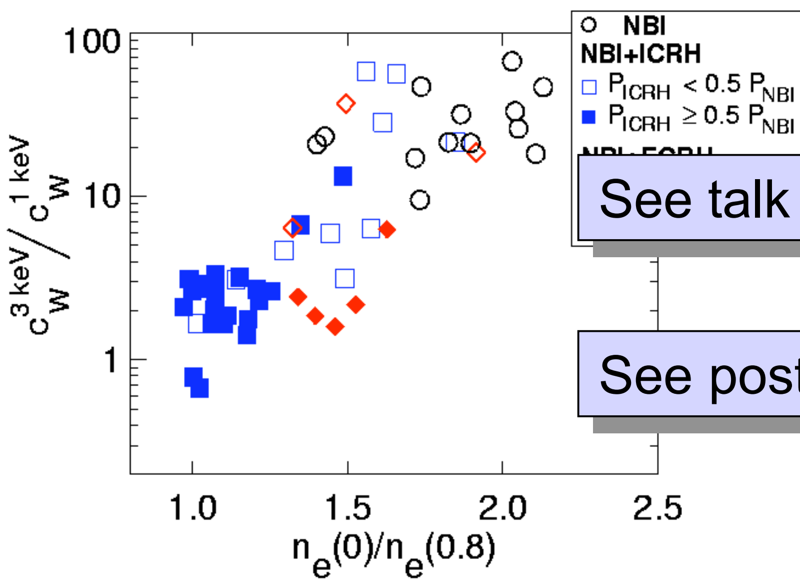
Integrated scenario

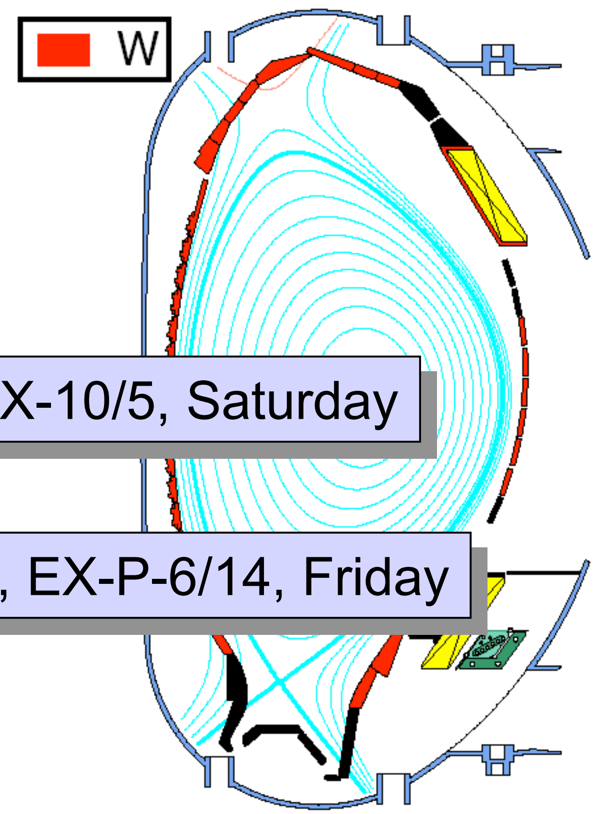
Tungsten as plasma facing material

In most discharges no problem (including W divertor operation)

65% (24.8 m² W covered)

Impurity problems if:
- Density peaking (neoclassical impurity pinch)





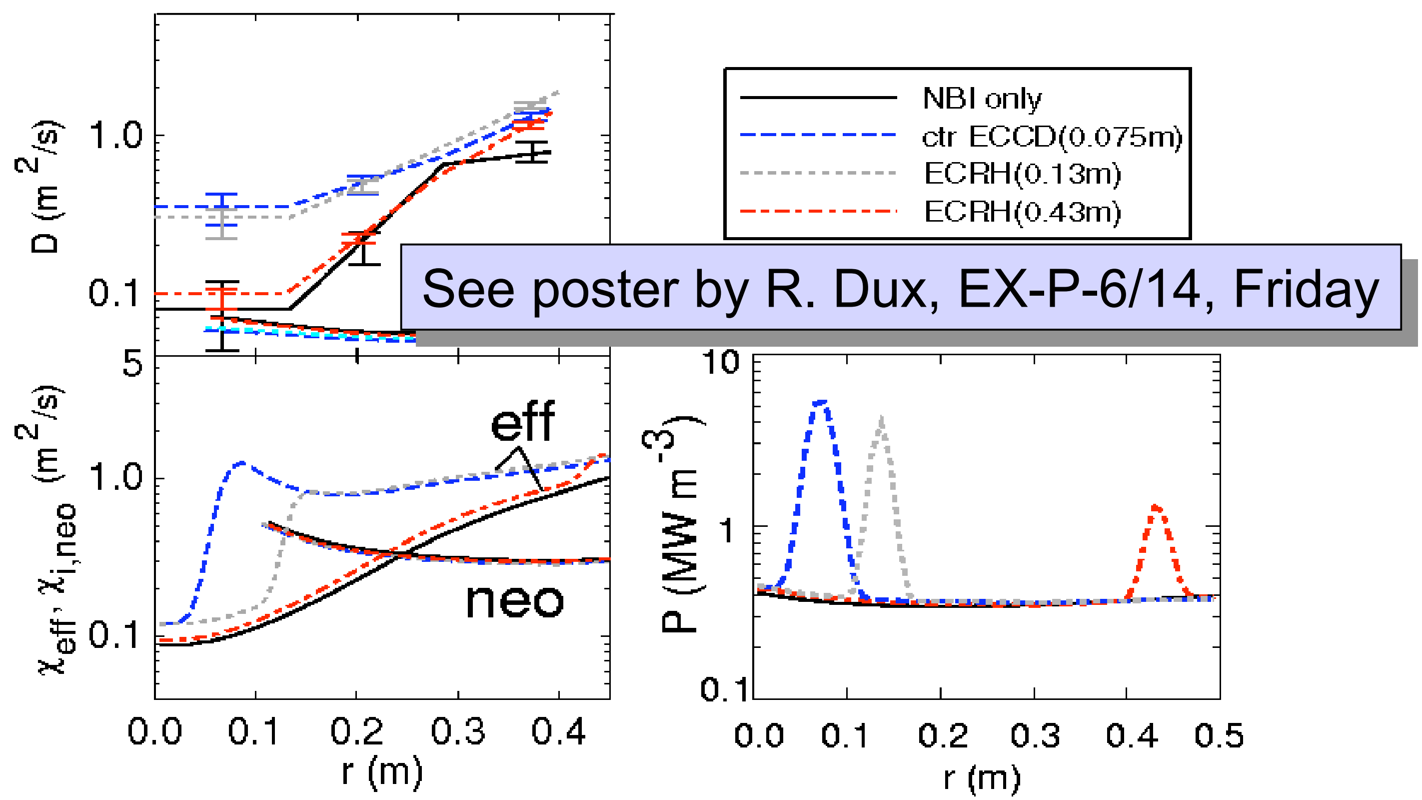
See talk by R. Neu, EX-10/5, Saturday

See poster by R. Dux, EX-P-6/14, Friday

- Limiter operation
- ELM free phases in H-mode

Control of impurity accumulation via central heating

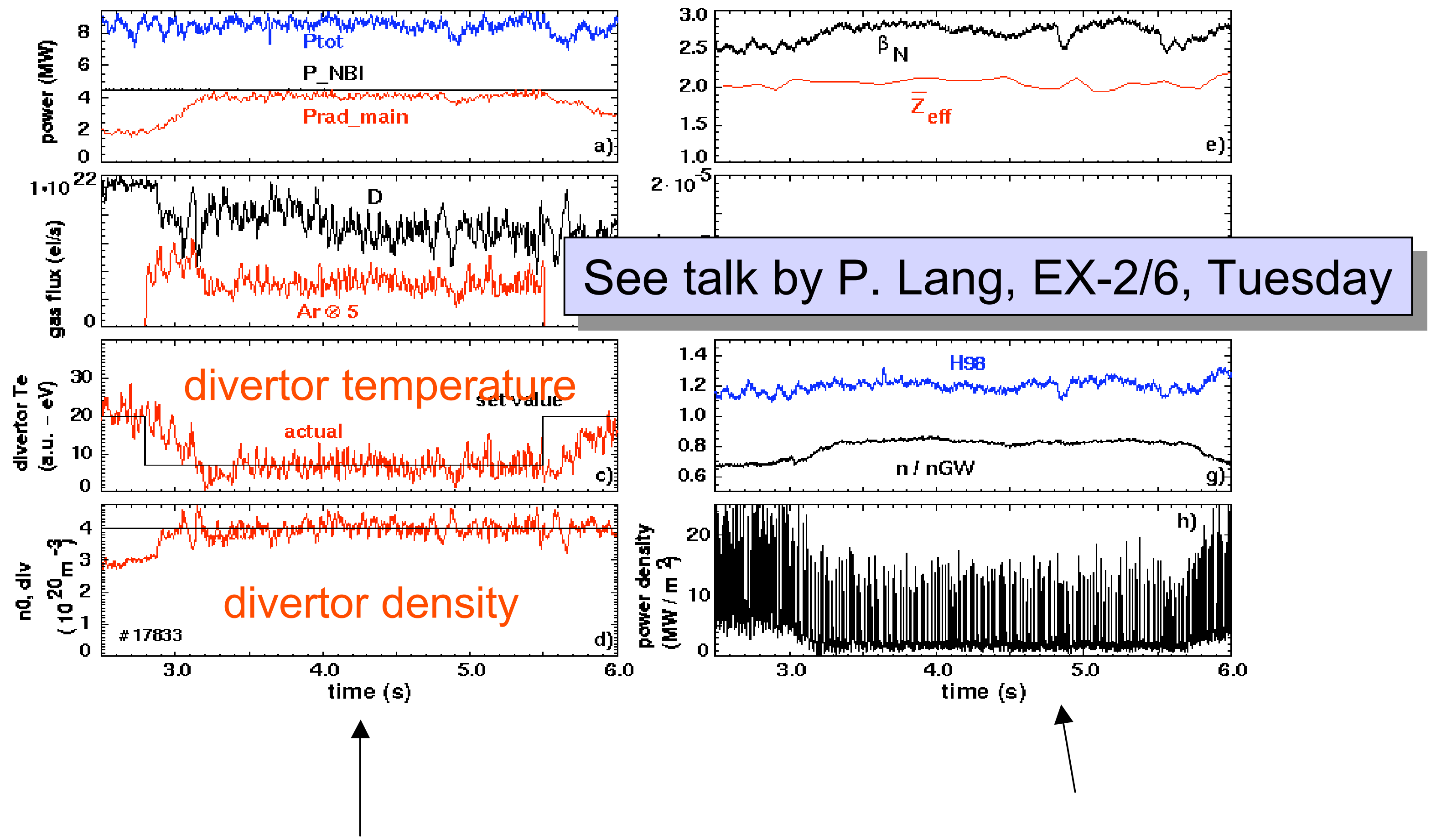
Si laser blow-off experiments



Effect of central heating on density peaking (neoclassical inward pinch) and on anomalous particle transport

Integrated exhaust scenario (towards full W machine)

Replace C by Ar for low divertor temperature ⇒ operation closer to H-L transition without ELM control high radiation, H-L transition



Control of divertor temperature by Ar seeding

ELM control by pellets

- Particle and energy transport
- Pedestal physics and ELM control
- Plasma wall interaction and impurity transport
- **Core MHD stability**
- Current profile tailoring

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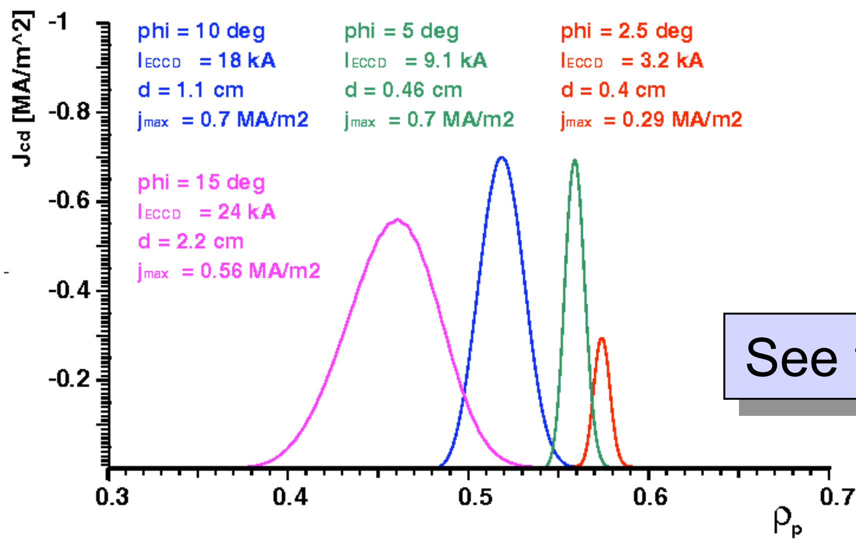
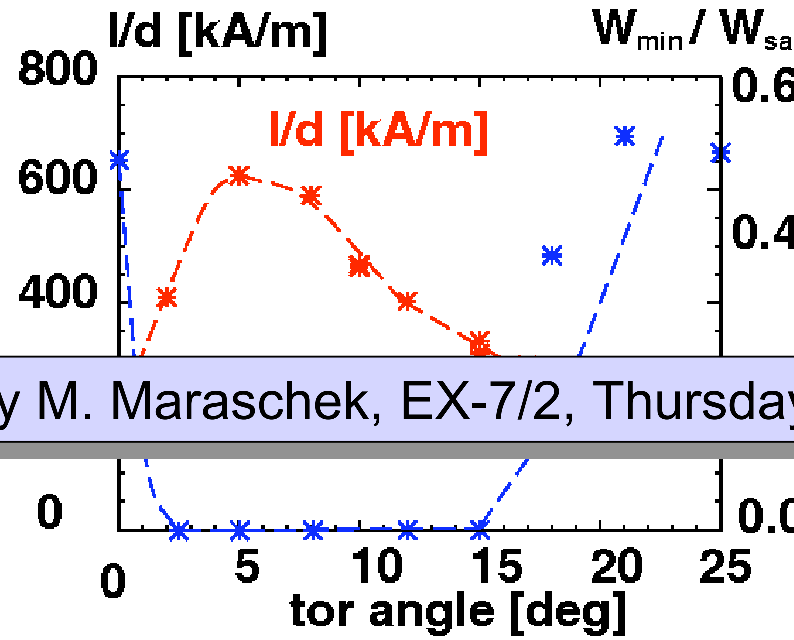
Integrated scenario

NTM stabilization: optimum launching angle

TORBEAM calculations





See talk by M. Maraschek, EX-7/2, Thursday

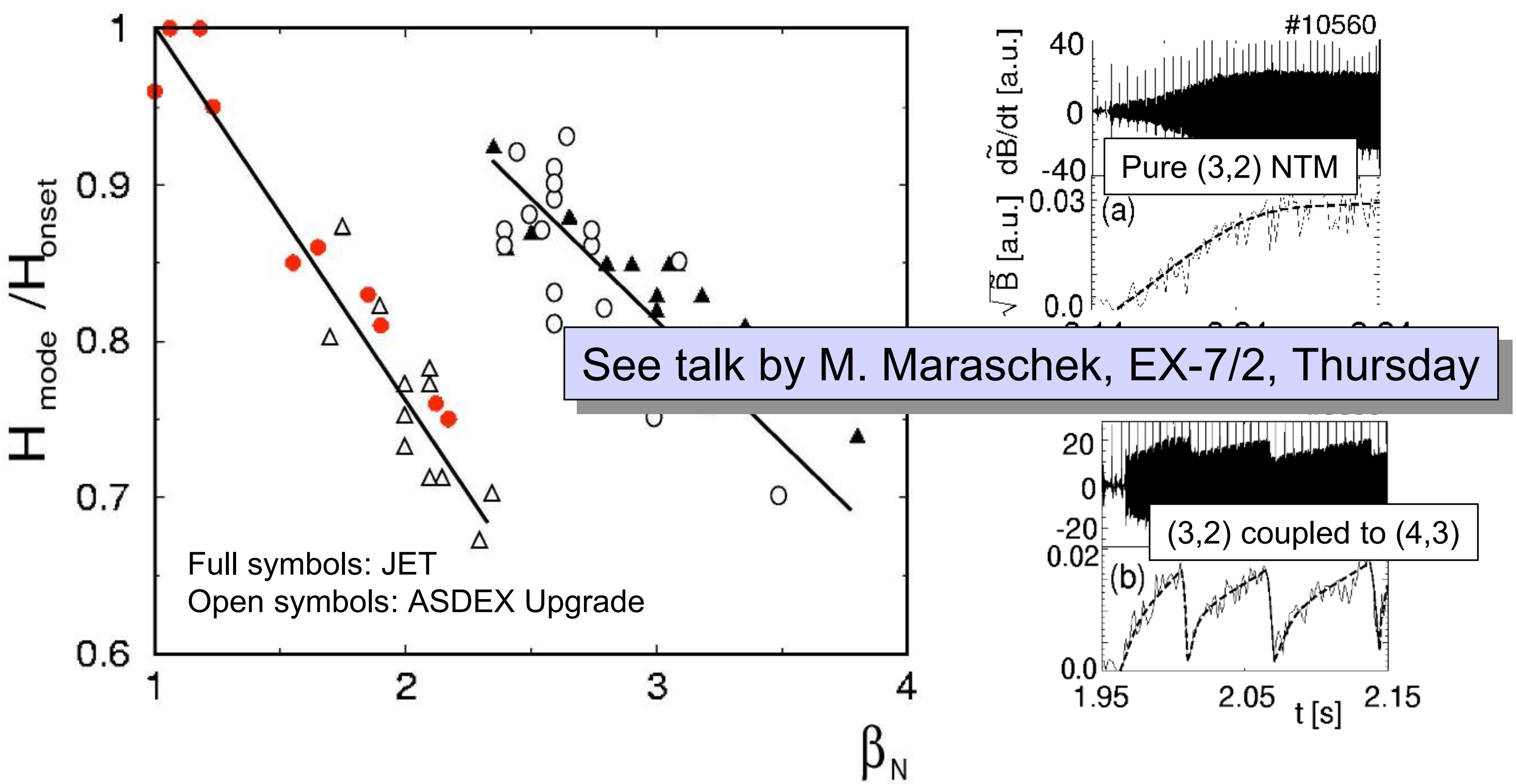
optimum launching angle: 5°, corresponds to 1 cm deposition width

Record values for complete NTM stabilization at given ECCD power:

(3,2) NTM: β_N=2.6 for P_{ECCD}=1.0 MW

(2,1) NTM: β_N=2.3 for P_{ECCD}=1.4 MW

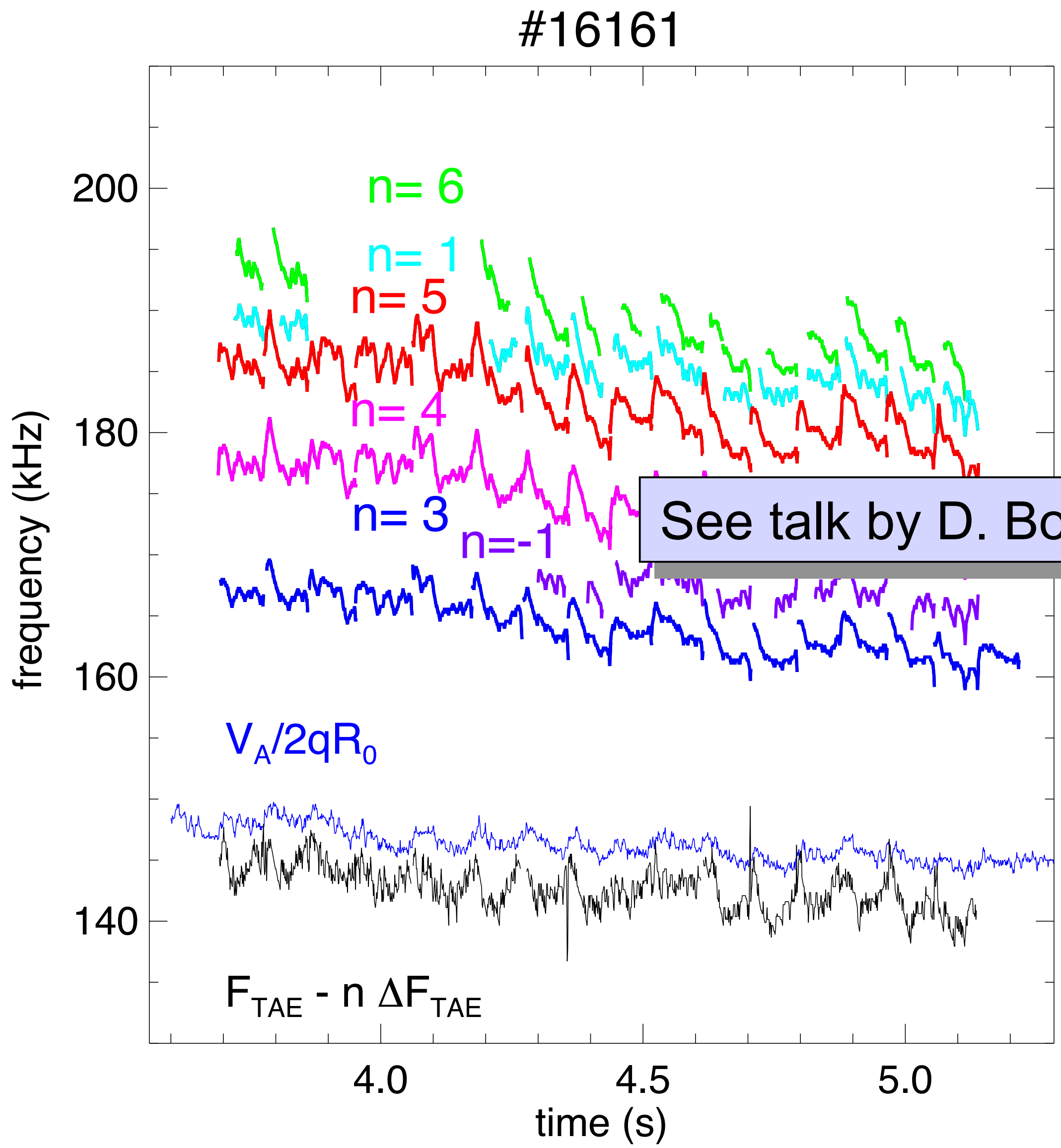
(3,2) NTMs in FIR regime for β_N > 2.3



FIR regime similar in dimensionless parameters (ASDEX Upgrade and JET)

Active stabilization on ITER only for (2,1) NTM needed?

TAE modes in low density ICRH heated discharges



See talk by D. Borba, EX-P-4/37, Thursday

- Particle and energy transport
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- **Current profile tailoring**

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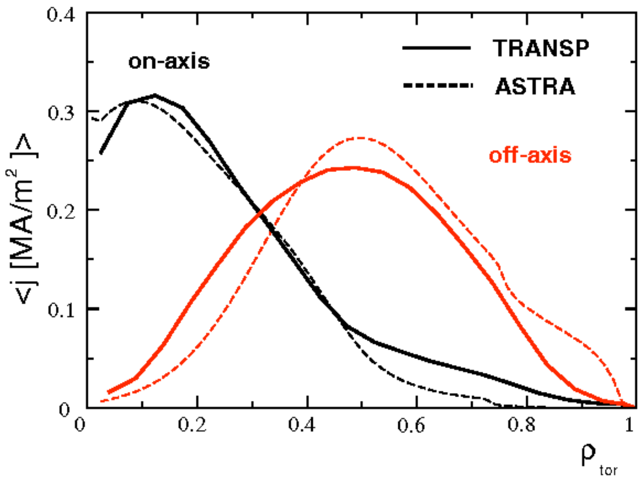
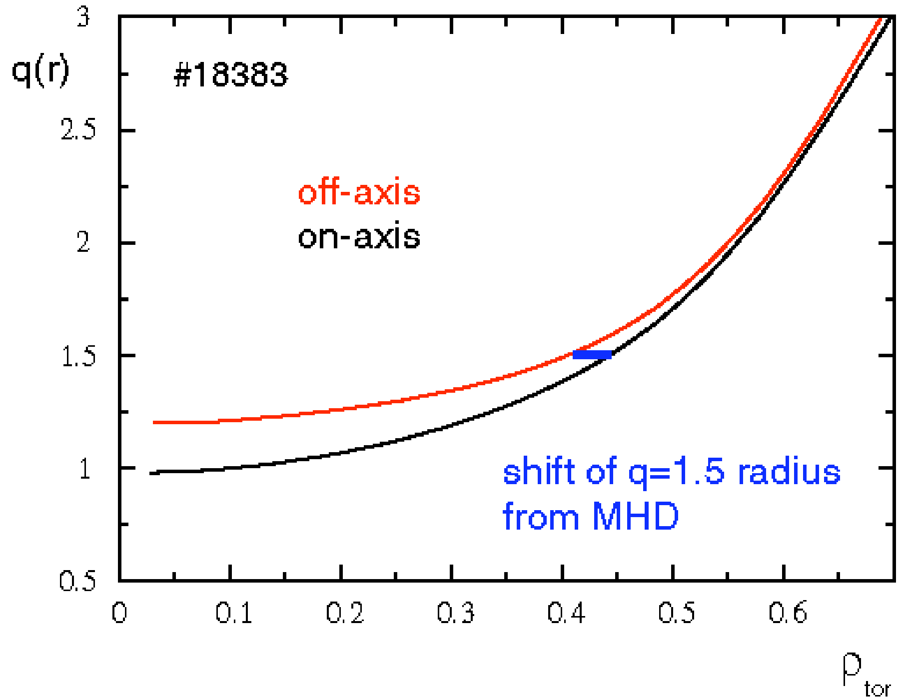
Integrated scenario

Off-axis NBI current drive on ASDEX Upgrade





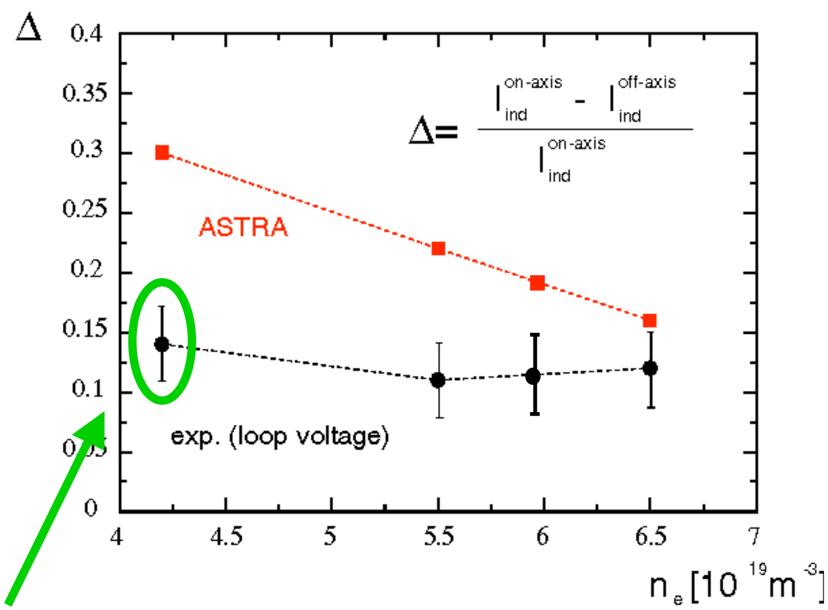
Current profile modification as predicted by TRANSP (MSE) – thanks to PPPL for support

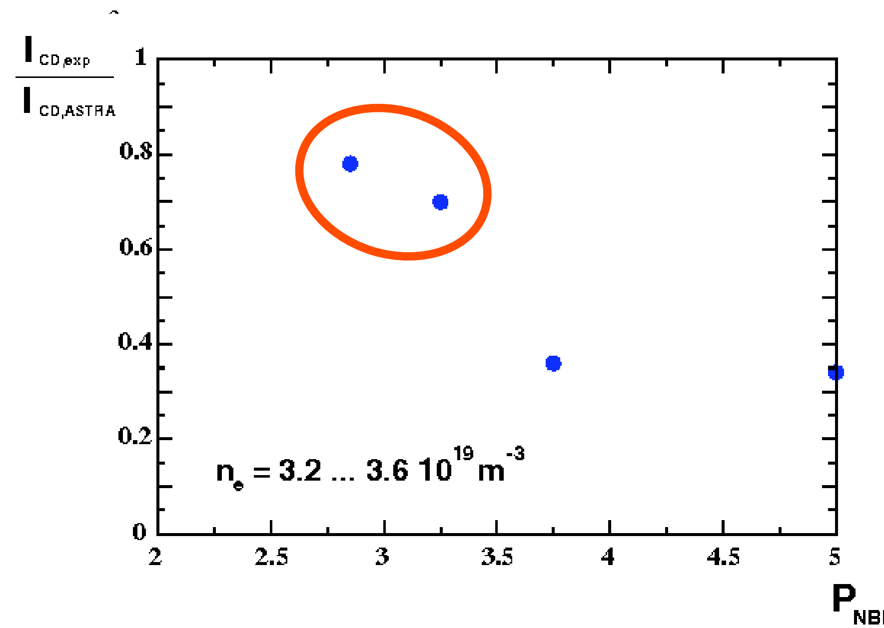
and consistent with shift MHD (shift of $r_{3/2}$)

But it only works at low heating power!

For large heating power:
- CD efficiency well below predictions (ASTRA,TRANSP)
- no change in q-profile

800 kA, 2.5 T, δ=0.15, 5 MW NBI





~100 kA

no change in q-profile for P_{NBI}~5MW

CD efficiency as predicted for low power only

Reduced CD efficiency due to redistribution of fast ions

Fast ion redistribution by Alfvèn waves? excluded:

- no Alfvèn waves observed
- $v_b < v_A$, no difference between experiments with full beam energy ($v_b > v_A/3$) and reduced beam energy ($v_b < v_A/3$)

Current redistribution by MHD? excluded:

- only (1,1) activity observed
- no influence of $q_a/q=1$ surface (q_a varied between 3.9 and 6.2)

Fast ion redistribution, correlated to intensity of thermal transport

Increase in heating power (independent of radial location and pitch angle reduces CD

- Particle and energy transport
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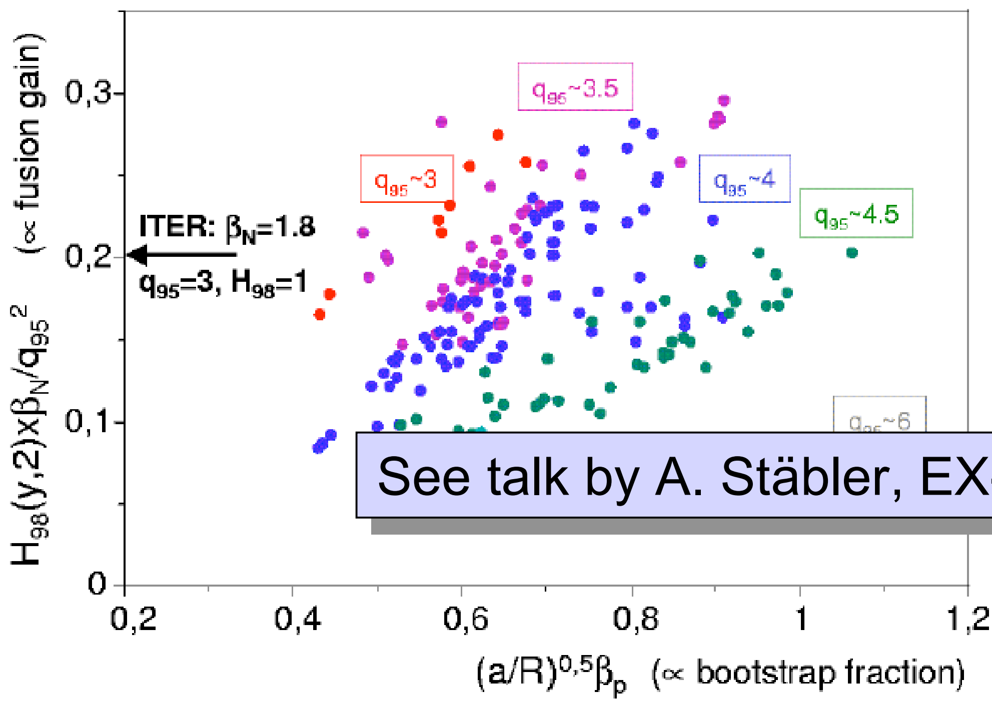
Integrated scenario

Improved H-mode: a hybrid scenario for ITER



See talk by A. Stäbler, EX-4/5, Wednesday

- attractive ITER scenario: higher Q at q_a~3 or longer pulses at q_a~4.5 (Q=10)
- demonstrated for : - ITER relevant υ^*
  - $n=n_{GW,}$ (type II ELMs)
  - $T_e=T_{i,}$ (so far only on ASDEX Upgrade)
  - all accessible ρ^* values
  - compatible with W walls

Overview of ASDEX Upgrade papers

A. Herrmann:	Wall and divertor heat loads, EX-2/4Rb	Tuesday
P.T. Lang:	Integrated exhaust scenarios with ELM control, EX-2/6	
W. Suttrop:	QH mode on ASDEX Upgrade and JET, EX-1/4	
A. Stäbler:	Improved H-mode - ITER hybrid scenario, EX-4/5	Wednesday
D. Borba:	TAE modes using IRCH, EX-P-4/37	Thursday
L.D. Horton:	Characterisation of H-mode barrier, EX-P-3/4	
M. Maraschek:	Active control of MHD instabilities, EX-7/2	
A.G. Peeters:	Understanding of transport phenomena, EX-P-3/10	
R. Dux:	Impurity transport and control, EX-P-6/14	Friday
A. Jacchia:	Electron heat transport, EX-P-6/17	
M. Mayer:	Carbon deposition and inventory, EX-P-5/24	
I. Nunes:	Density profile evolution, EX-P-6/20	
R. Neu:	Tungsten for main chamber and PFC, EX-10/5	Saturday

Are there inconsistencies with other experiments?

Slowing down of NBI ions is thought to be classical:

TFTR:

• NBI at r/a=0.5, 2 MW beams with 95 keV, no central heating
(nearly no radial diffusion of fast ions: $D < 0.05\ m^2/s$), Efthimion IAEA 1988

JET, TFTR:

• Slowing down of 1 MeV tritons from d(d,p)t :
- in low temperature plasmas: classical slowing down
- for long slowing down time: $D \approx 0.1\ m^2/s$
(Conroy EPS 1990, Scott IAEA 1991)

DIII-D:

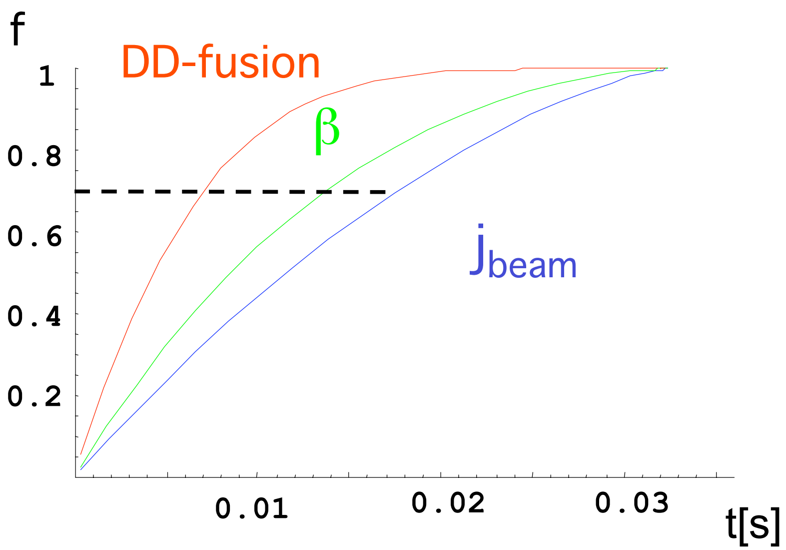
• anomalous fast ion redistribution needed to match stored energy and neutron rate for NBI heating in TRANSP simulations: $D \approx 0.3\ m^2/s$

Are there inconsistencies with other experiments?

Slowing down of NBI ions is thought to be local, usually concluded from :

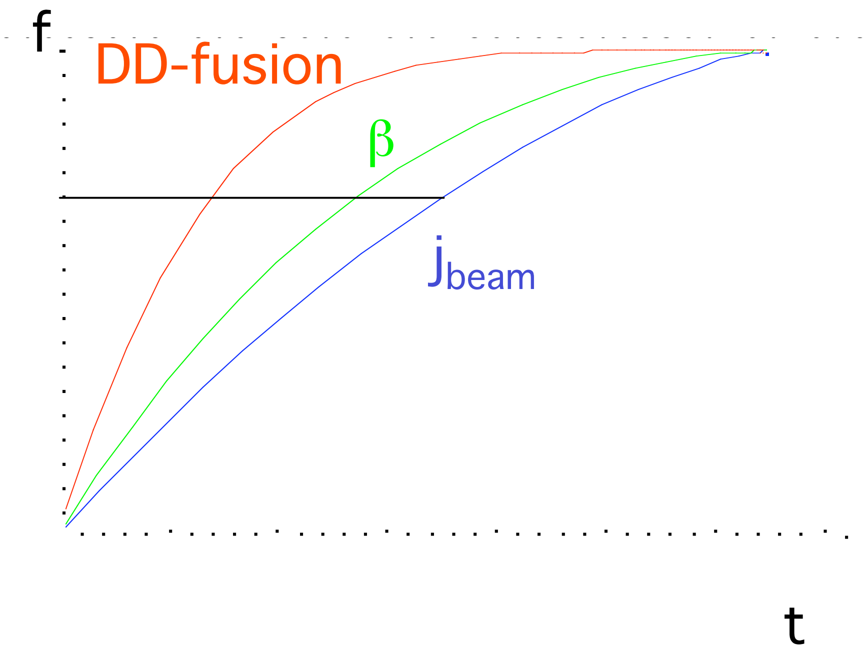
- neutron rates
- heat deposition (mostly in low heat flux discharges)

But beam current particularly susceptible to diffusion:
Slowing down particles contribute substantially longer to beam current than to energy density or fusion rate



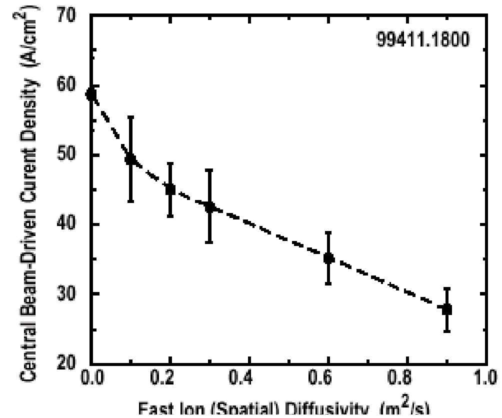
D-beam, E_{beam}=92keV,
T_e= 1keV, n=$5x10^{19}m^{-3}$)

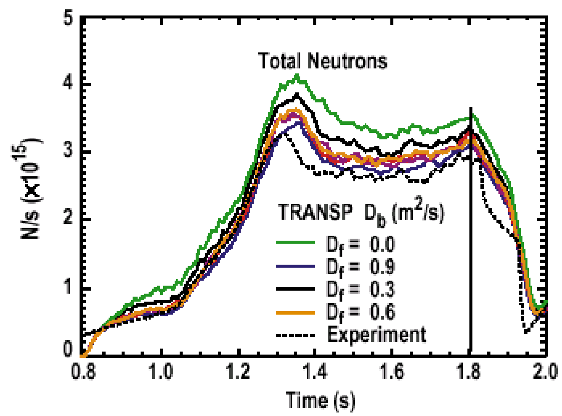
beam current particularly susceptible to diffusion: slowing down particles contribute substantially longer to beam current than to energy density or fusion rate



fractional contribution f of fast particles to DD-fusion, β, and beam current during first t seconds of their slowing down history

(D-beam, E_{beam}=92keV,T_e= 1keV, n=5x$10^{19}$$m^{-3}$)



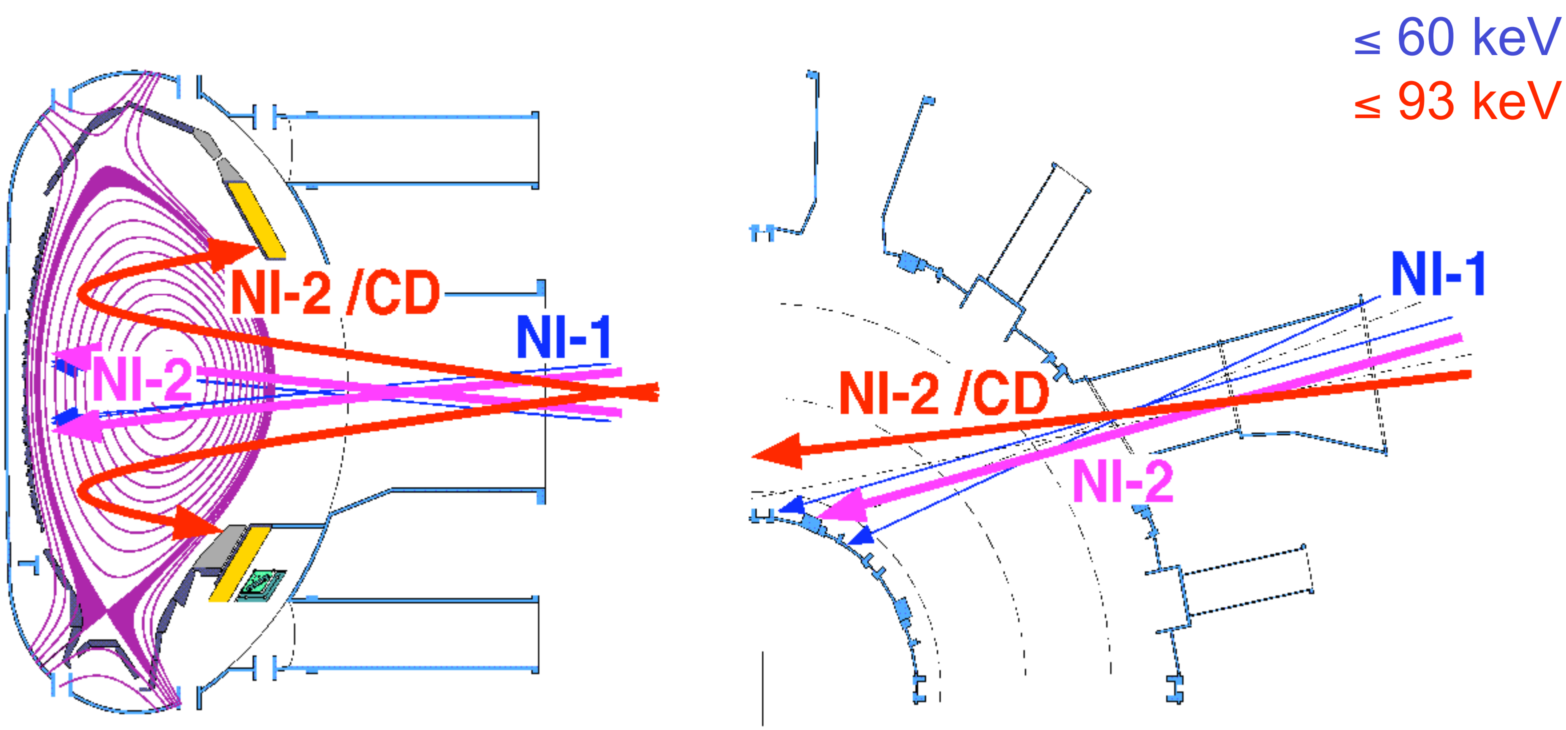


DIII-D: D_b=0.9m^2/s induced change:

<20% in f_{DD}

>50% in f_{jbeam}

NBI current drive system on ASDEX Upgrade

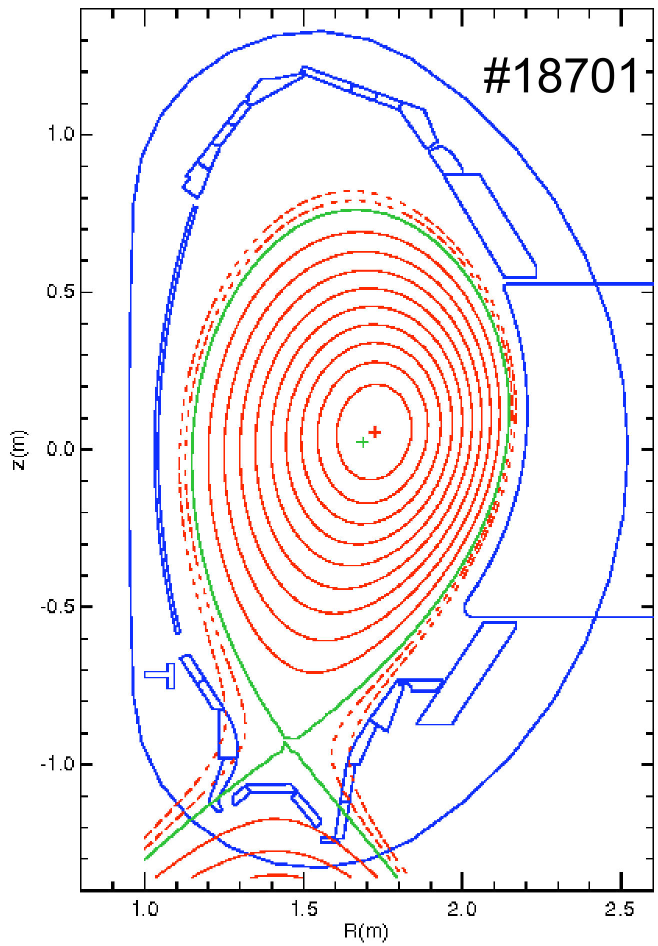


Re-direction of neutral beam injection system

- strong off-axis deposition by tilt of injection angle
- significant current drive at half radius expected

Higher beam power possible for higher triangularity

low δ (δ ≈ 0.15)



high δ (δ ≈ 0.4)