ASDEX Upgrade results and future plans

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Outline

Basic properties of the ASDEX Upgrade (AUG) tokamak

machine parameters, heating and CD systems, plasma facing components

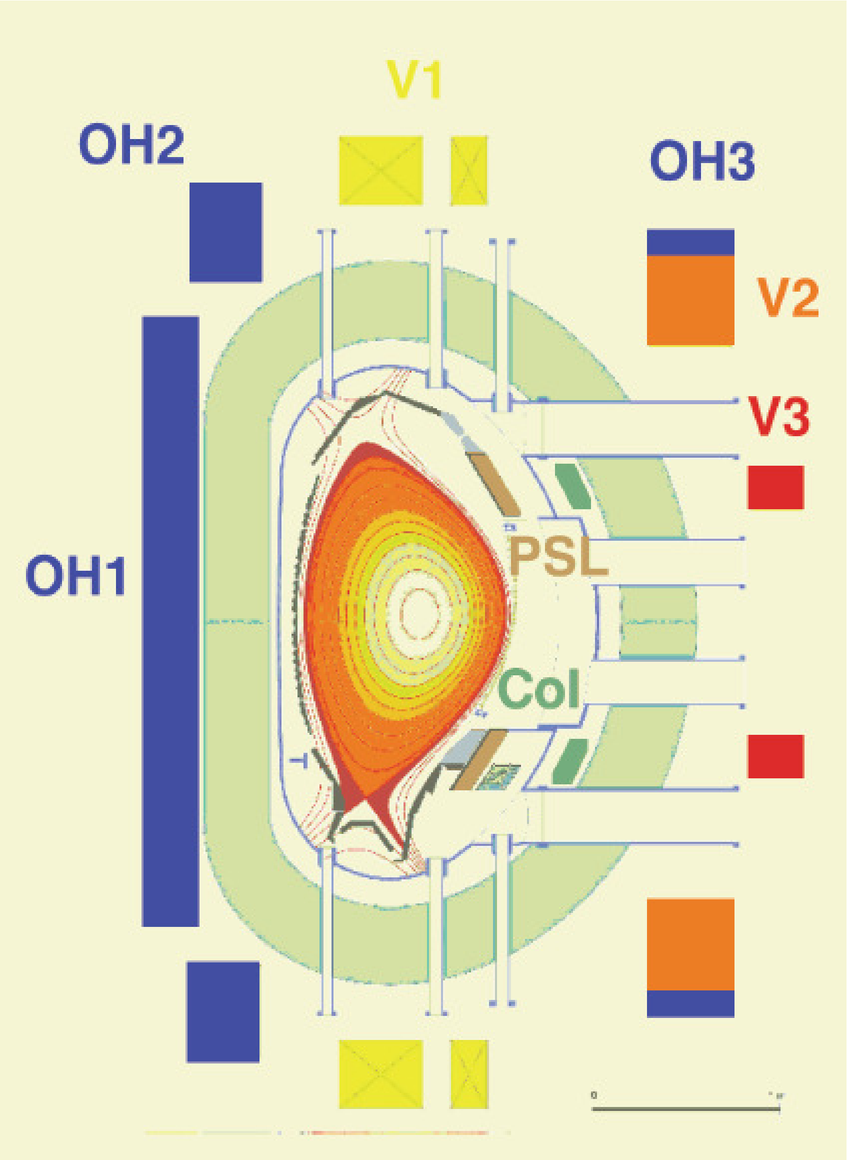
what makes AUG different from other mid-size tokamaks ?

Recent achievements and planned extensions

- divertor development
- improved ICRF antenna design
- ECRH extension and physics studies
- ELM mitigation by magnetic perturbations

Future ASDEX Upgrade planning

AUG cross section and poloidal field coil system



The PF coils are situated outside
the toroidal field coils
(like in ITER, and probably in DEMO)

R_{major}= 1.65 m

Actual heating and current drive systems

2 neutral beam injectors (60+90 kV),
4 sources each á 2.5 MW

4 ICRF generators á 2 MW, 4 antennas

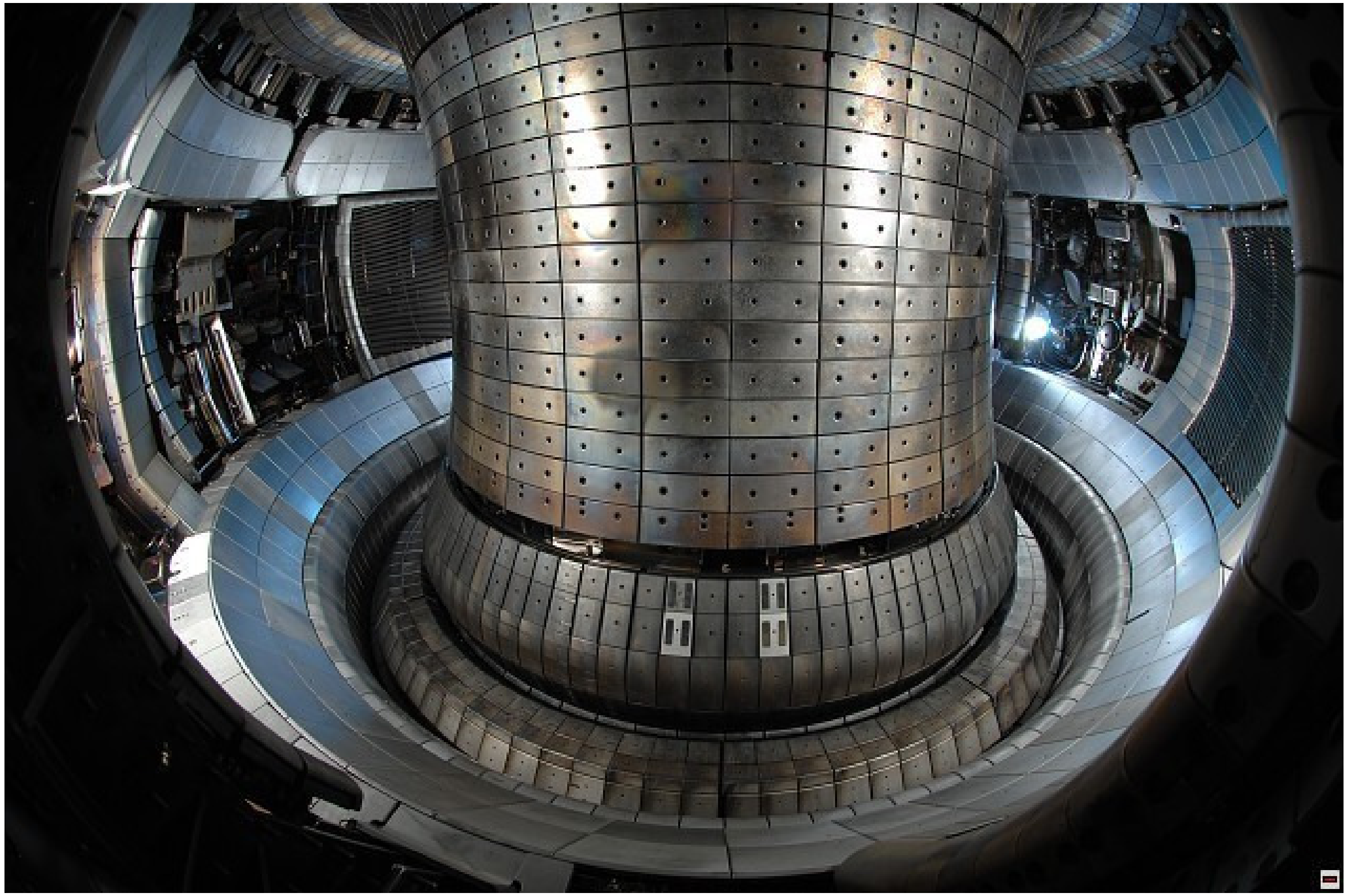
4 ECRH I gyrotrons 0.5 MW, 2 s (140 GHz)
3 ECRH II gyrotrons 1 MW, 10 s
(140 GHZ, 0.8 MW 105 GHz)

4th step-tunable (105 GHz, 140 GHz) ECRH II gyrotron
scheduled end 2011

Power to plasma	Heated species
20 MW	ions+electrons
6 MW	electrons+ions
4 MW	electrons

20 MW used simultaneously with feedback controlled N seeding, so far

All plasma facing components are clad with tungsten

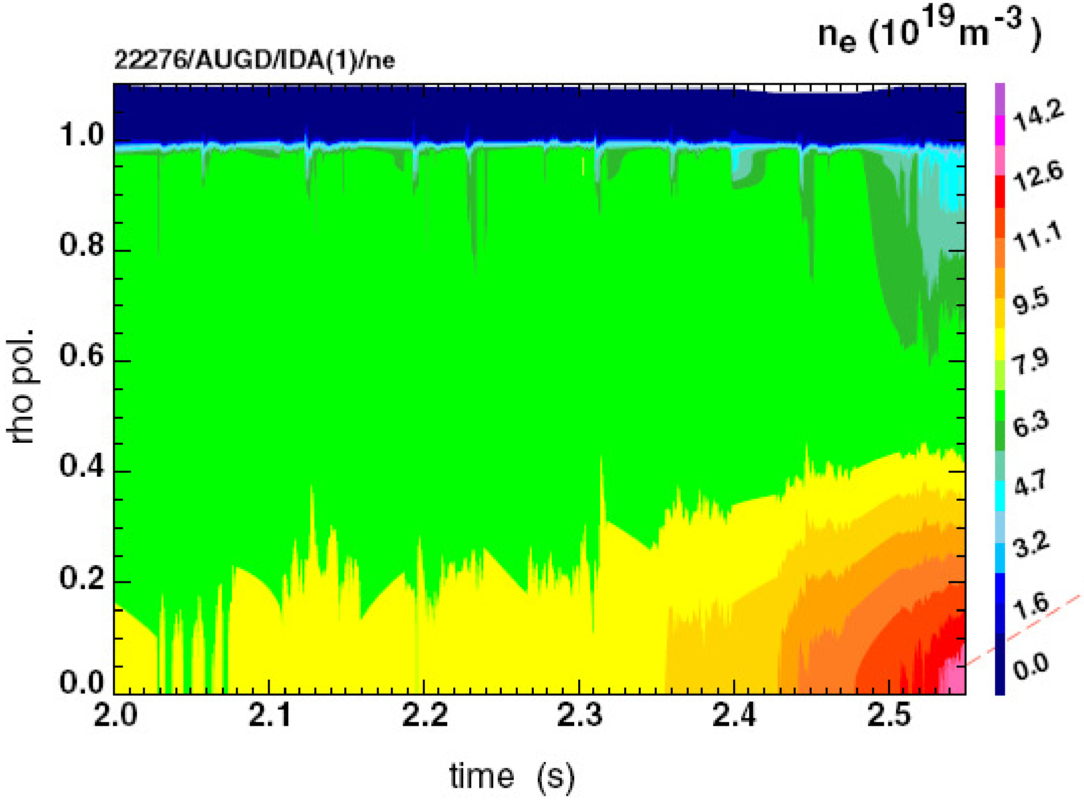


W PFCs require adaption of operating scenarios: W accumulation avoidance

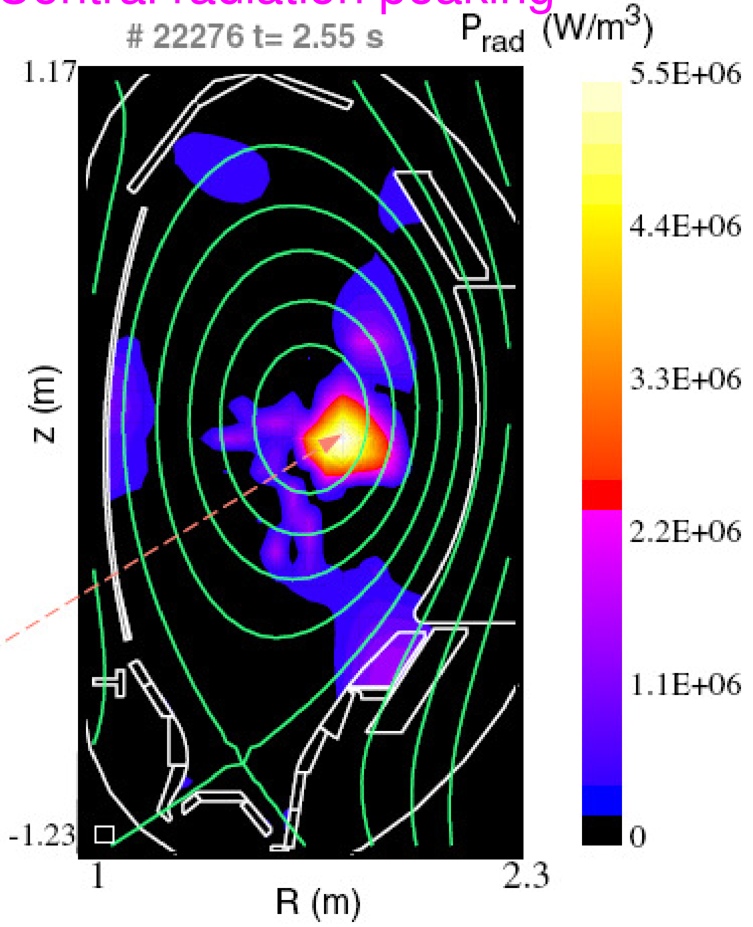
Central tungsten accumulation

… occurs if central heating and/or ELM flushing not sufficient

Electron density peaking



Central radiation peaking



Counter-measures:

+ increase central heating

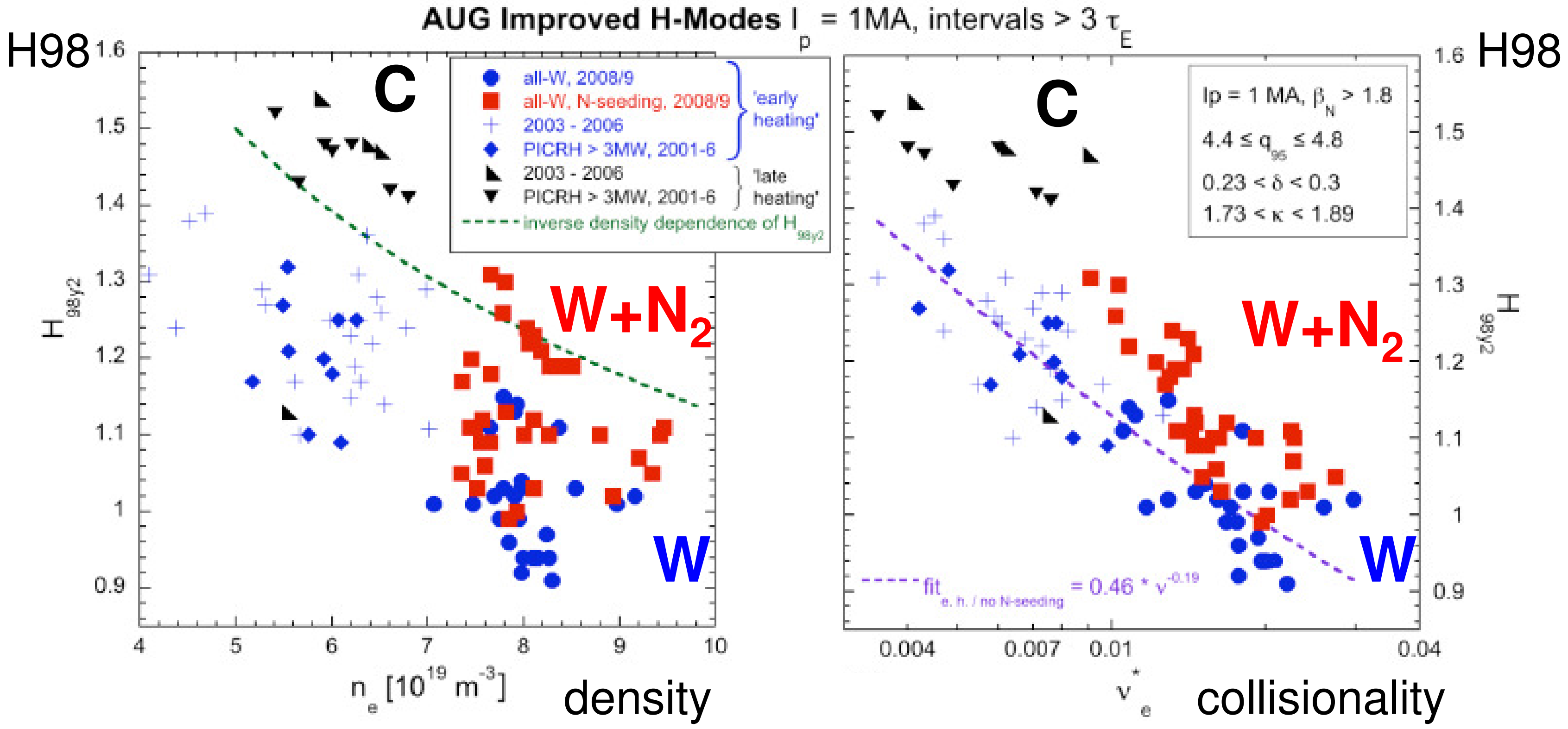
+ increase ELM frequency by D puff

Implications of the tungsten PFCs on operation space

ASDEX Upgrade works with slightly higher densities compared to carbon tokamaks

- improved H-mode at slightly higher core collisionalities

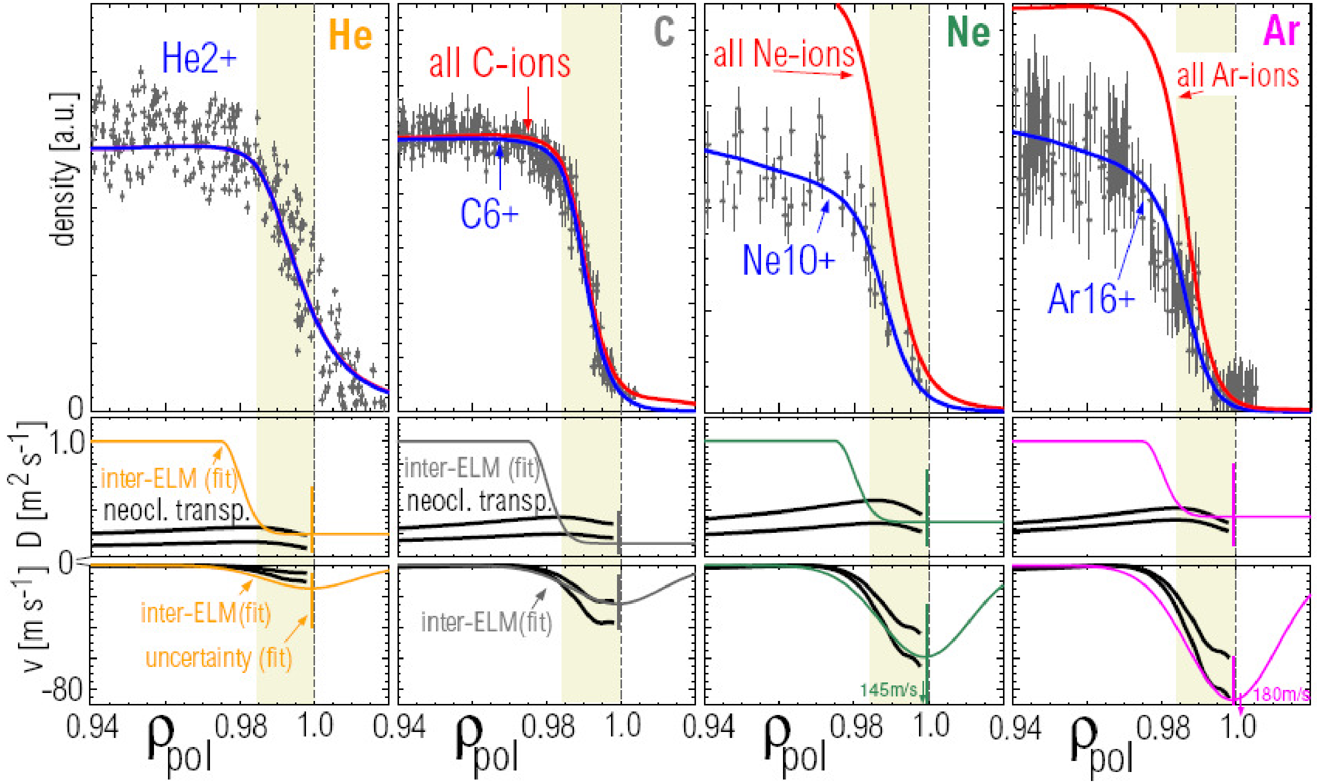
+ power exhaust controlled and mitigated



- W does not produce wall pumping like C
- some D puff necessary for W accumulation control

Core W content depends on pedestal transport:
neoclassical W inward drift and ELM flushing

Impurity ion transport in ETB is neoclassical – strong W inward flux



impurity peaking $n_{pedestal}/n_{sep}$

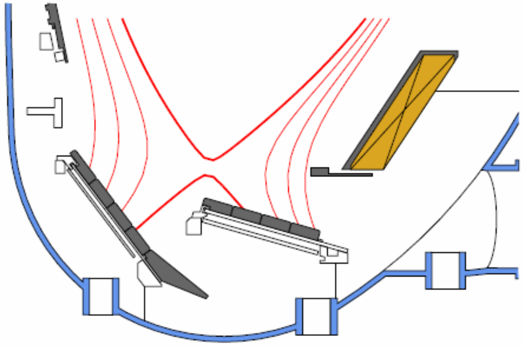
- ELM flushing required to limit pedestal peaking of high-Z impurities
- deuterium puffing is the standard tool to ensure sufficiently high ELM frequency

Next topic:

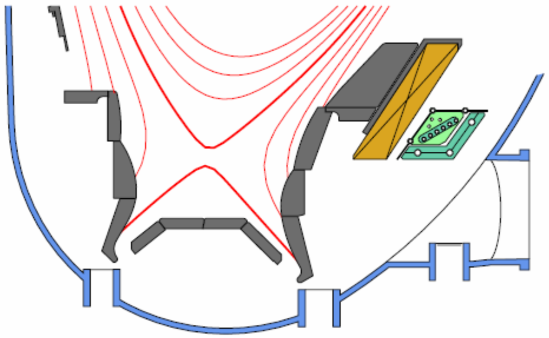
Divertor development

- Over its 20 years of operation, several upgrades of the AUG divertor occured

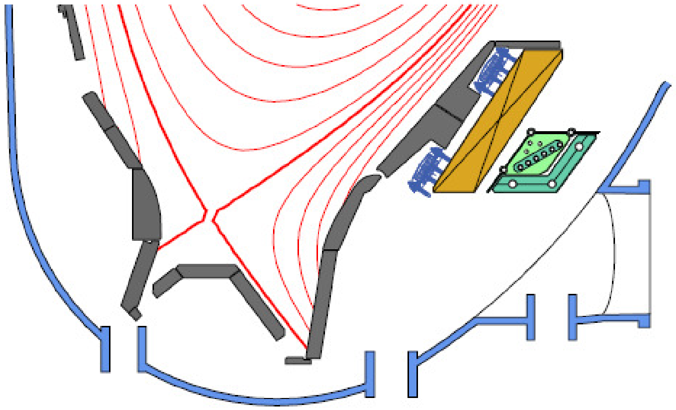
Divertor evolution: several stages of improvement



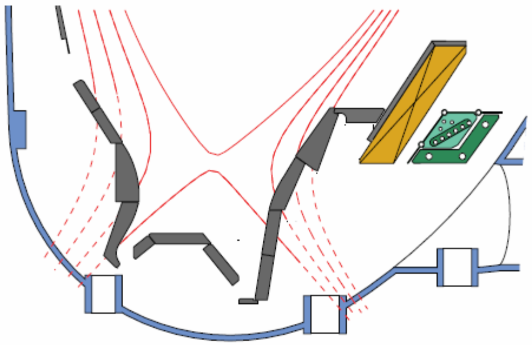
DIV I (1991-1997)



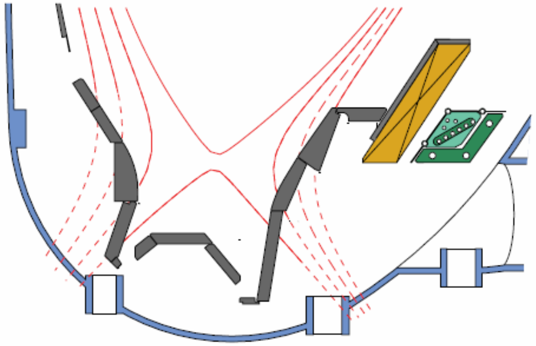
DIV II (lyre: 1997-2000)



DIV IId (2010-...)



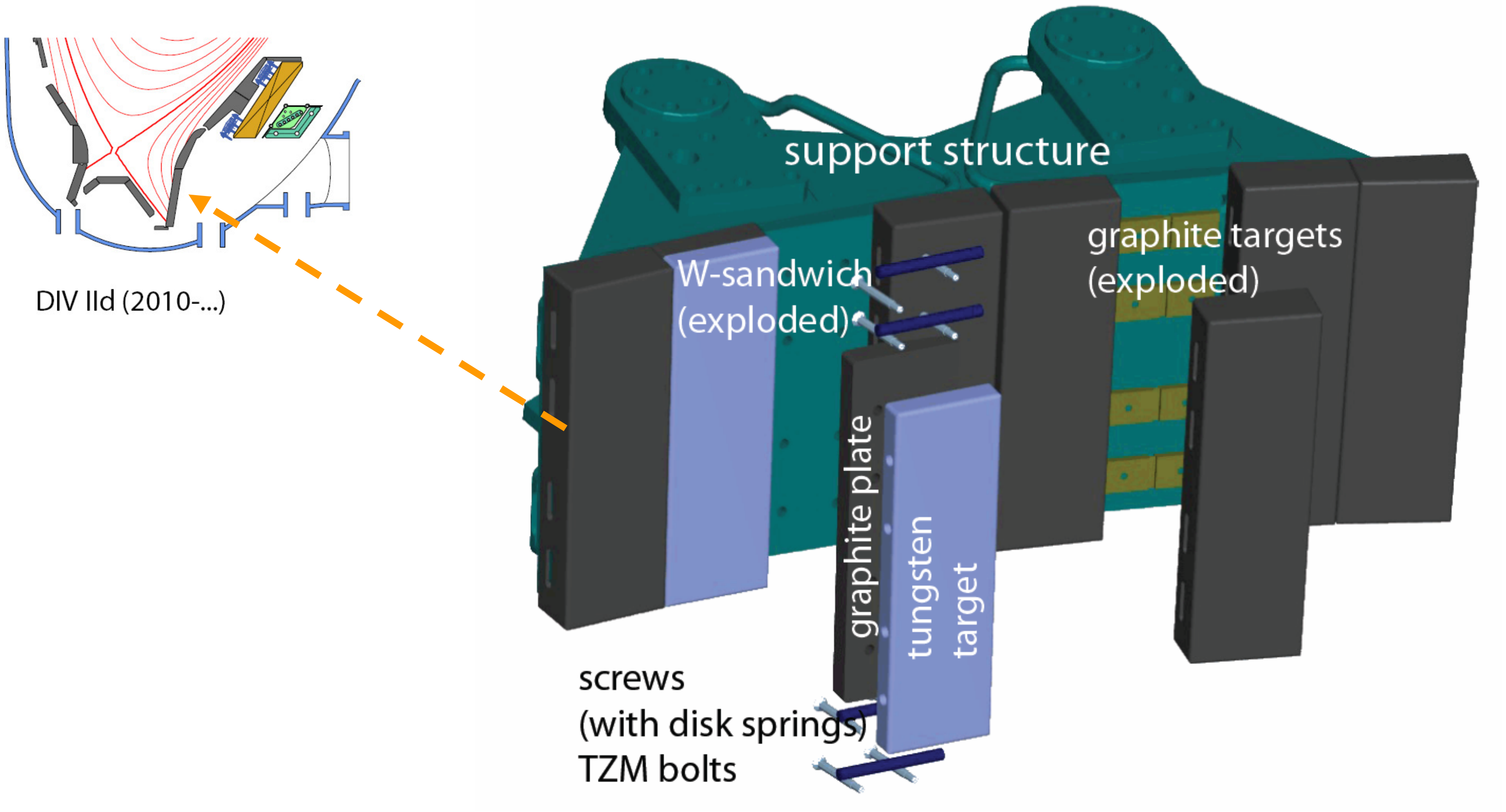
DIV IIb (2000-2006)



DIV IIc (2007-2009)

Lessons learned:
a divertor should be closed, but not too tight or complicated, and without leading edges

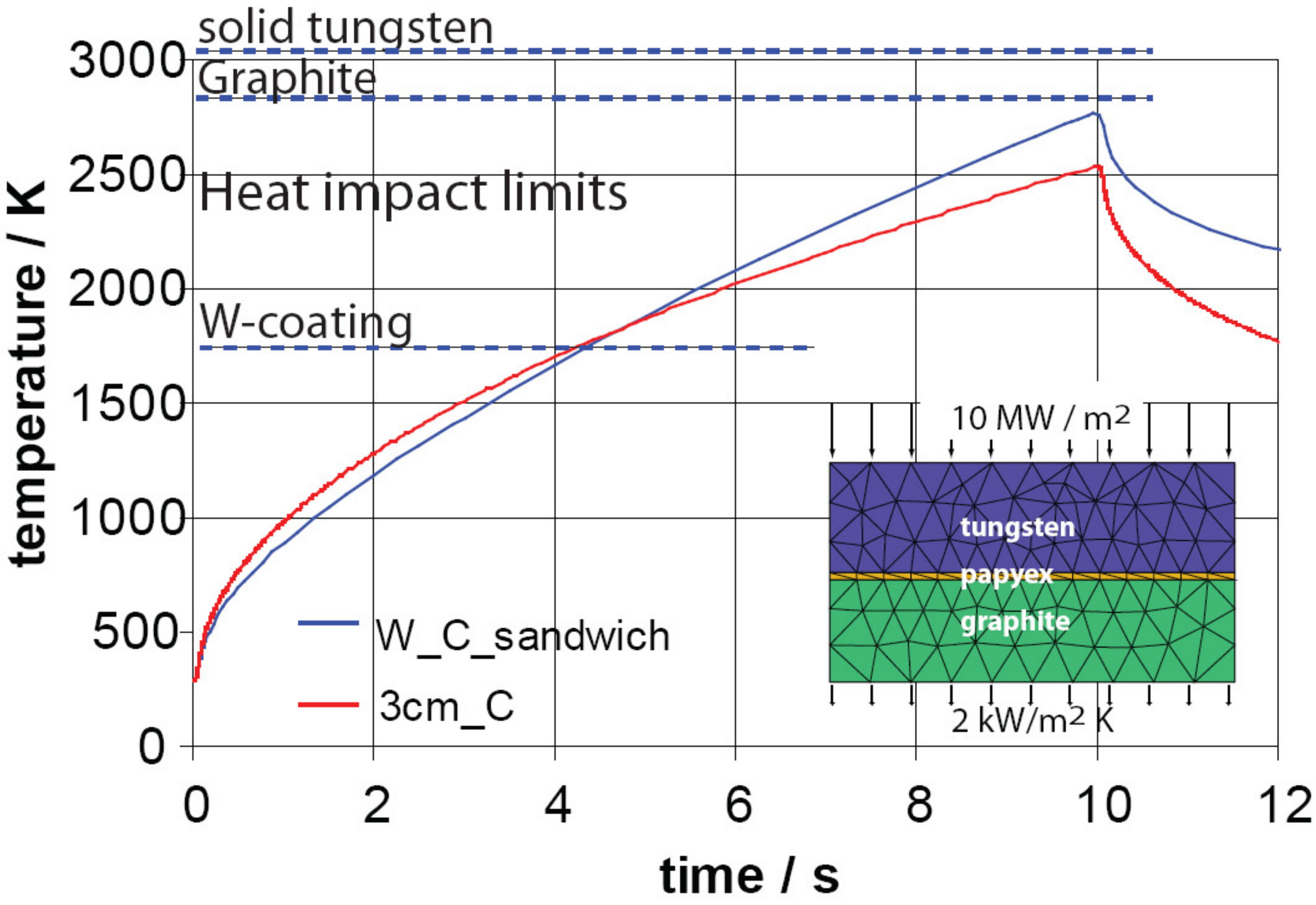
Next divertor stage: a solid tungsten outer target (end 2012)



A W-C sandwich structure is used to reduce weight.

The solid W will allow higher surface temperatures compared to a W coating

Improved heat impact limit with the solid W divertor III



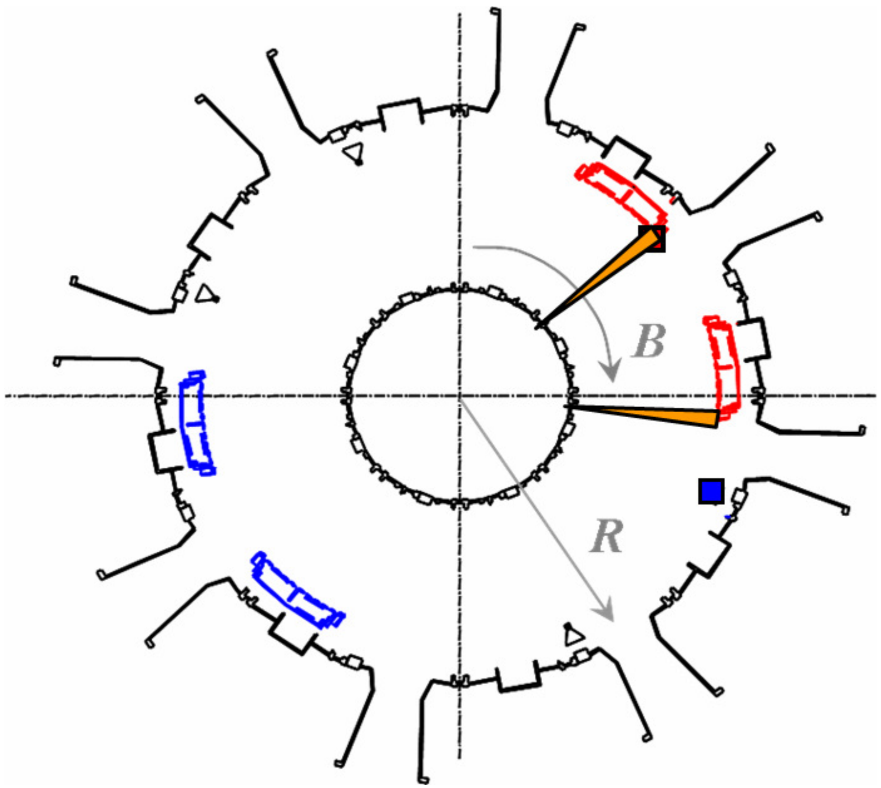
note that the AUG divertor is inertially cooled

Next topic:

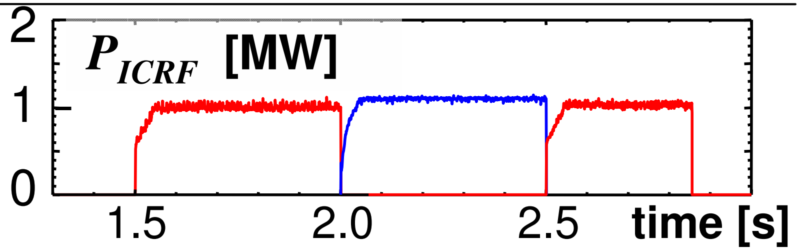
ICRF physics and antenna optimization

- ICRF operation with tungsten antenna limiters leads to high W sputtering rates
- these cause enhanced radiative losses

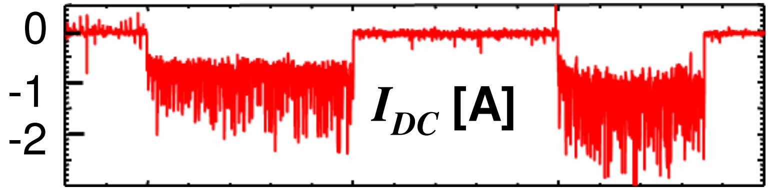
ICRF physics and antenna optimization to achieve better high-Z compatibility



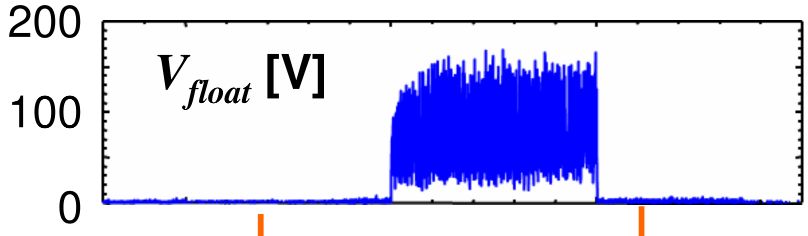
- local effect
- electrons are driven to ground
- RF $E_{\parallel}$ fields drive rectified sheaths



electron current to antenna frame

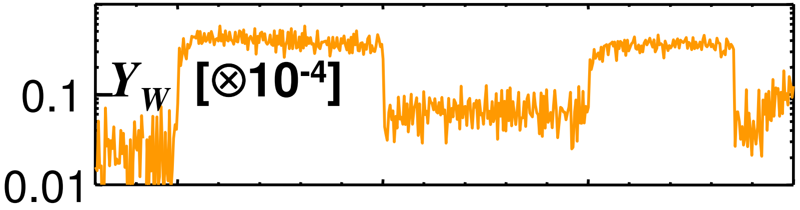


rectified potential in plasma



ion acceleration by rectified sheaths

increased sputtering yield $Y_W = G_W/G_H$:



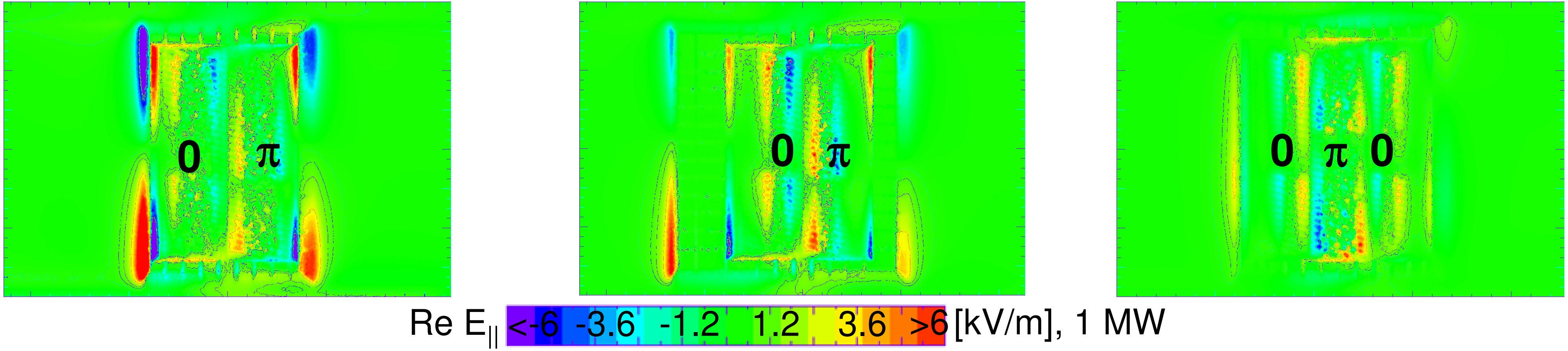
ICRF physics and antenna optimization:

HFSS code calculations of near fields

Broad limiter antenna (2011)

Original antenna

3-strap antenna
(2013 ?)



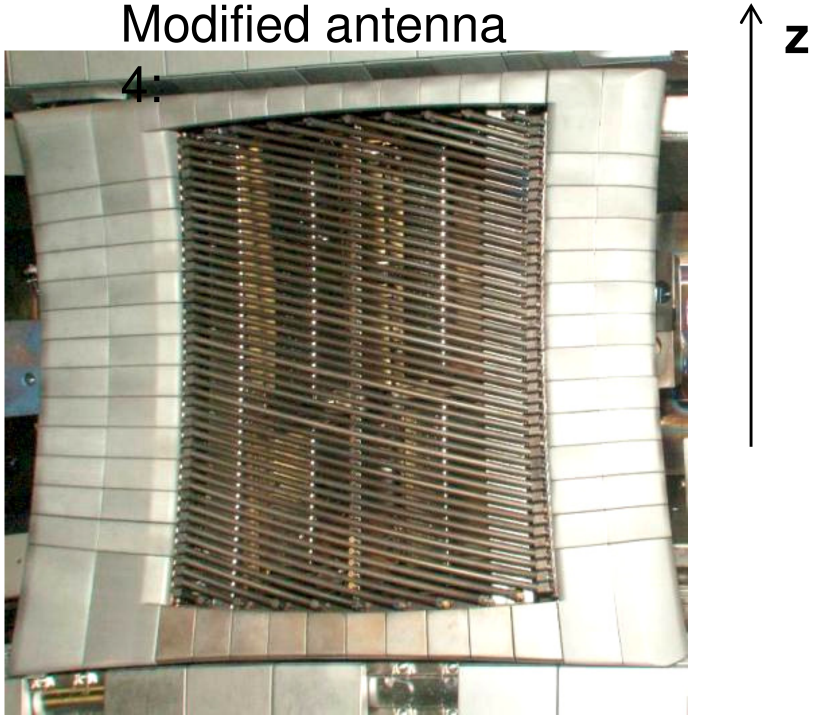
two 3-strap antennas as next step

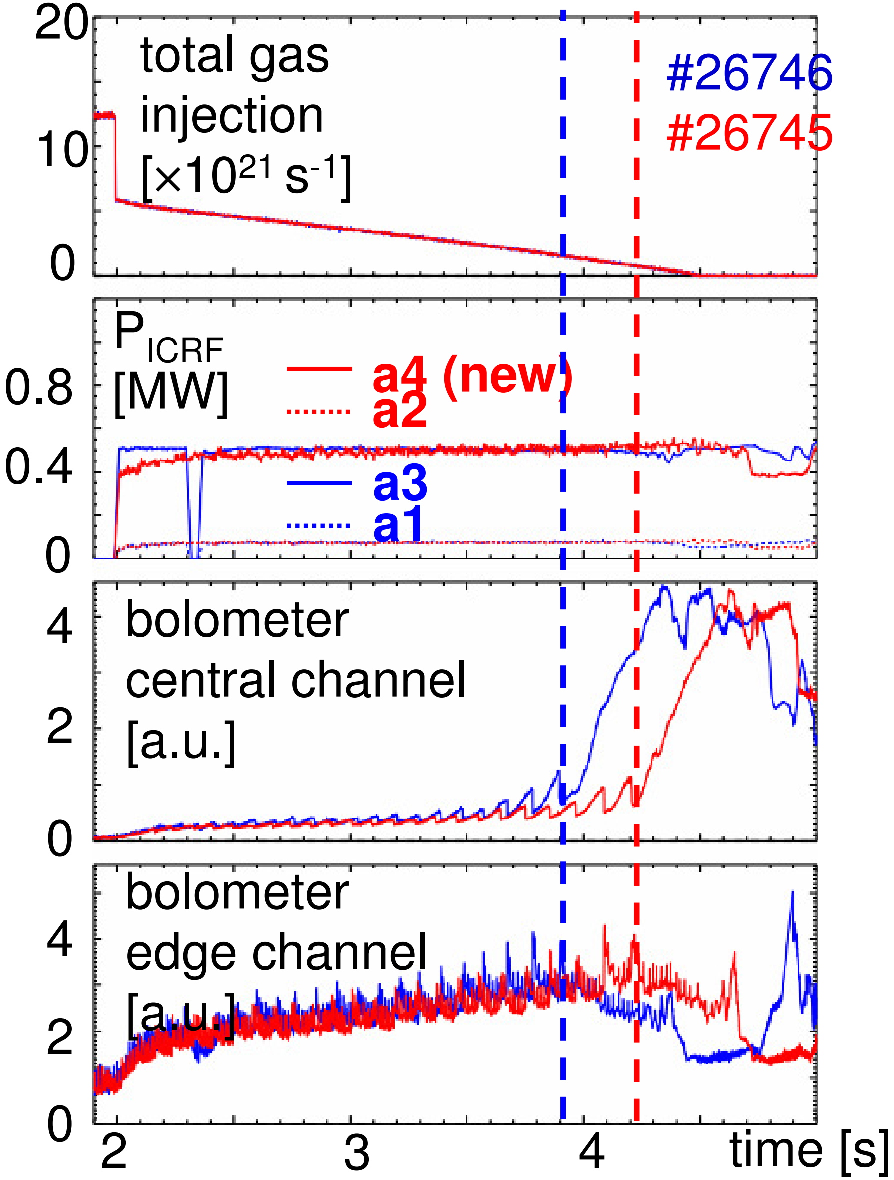
- need to control phasing and amplitude
- allows scan of amplitude/phase balance

in collaboration with ENEA/PoliTo

Broad limiter ICRF antenna shows better W accumulation behaviour (code benchmark step)

Modified antenna 4:





- W accumulation appears with new antenna at smaller gas injection rate
- new antenna has better balance central heating / W source
- → proceed to 3-strap antenna

Next topic:

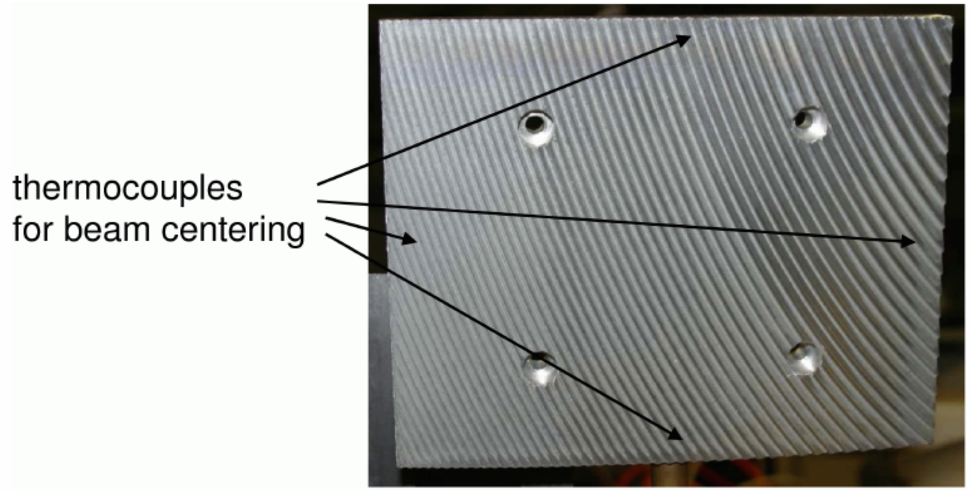
ECRH extension and transport studies

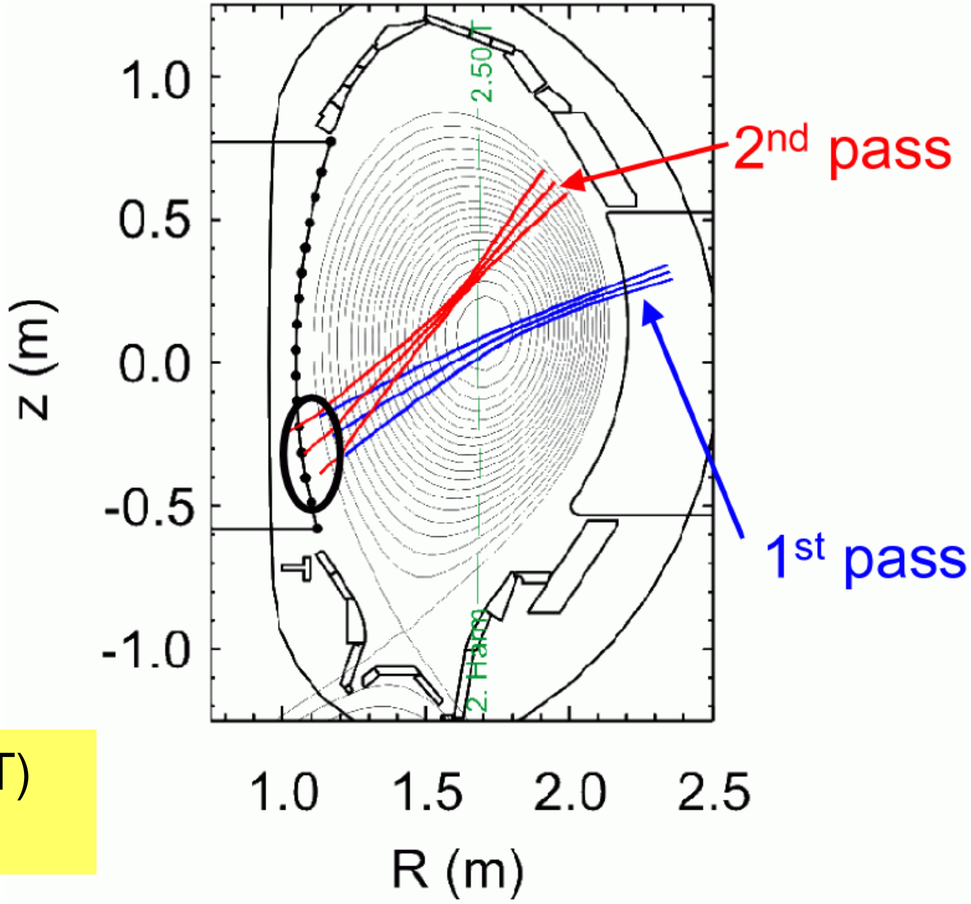
ECRH is a highly versatile tool for
- central heating
- MHD control
- current drive
- global and local transport studies ←

Several ECRH schemes developed and used in AUG: X2, O2, X3, O1 mode

Special measures required for low single path absorption of X3, O2 and O1 modes

holographic focusing mirror for O2-mode

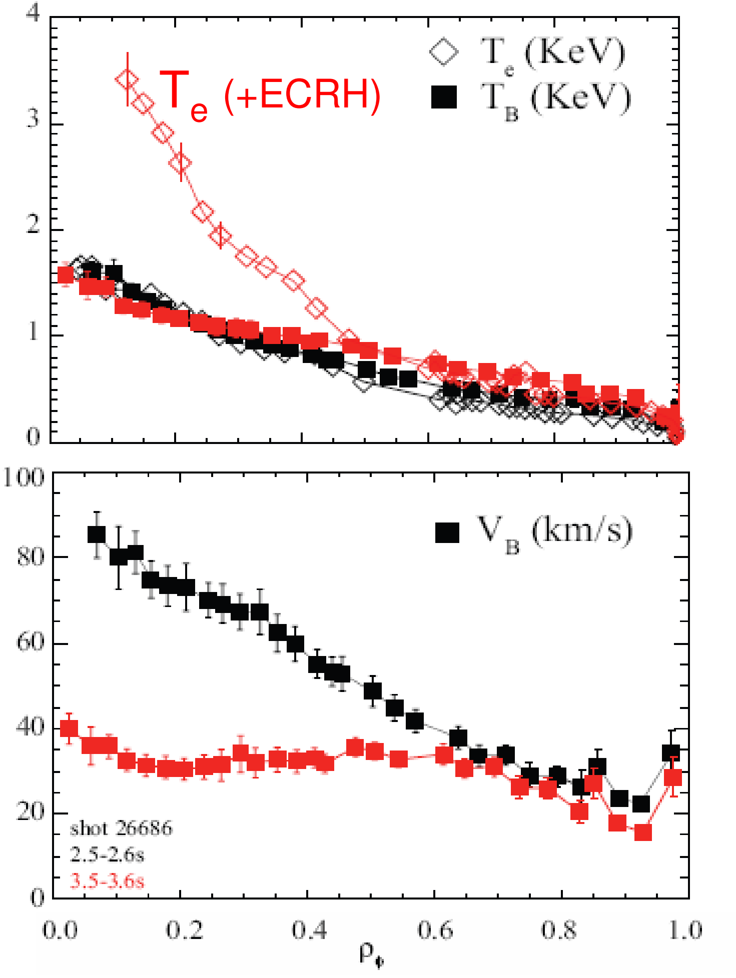


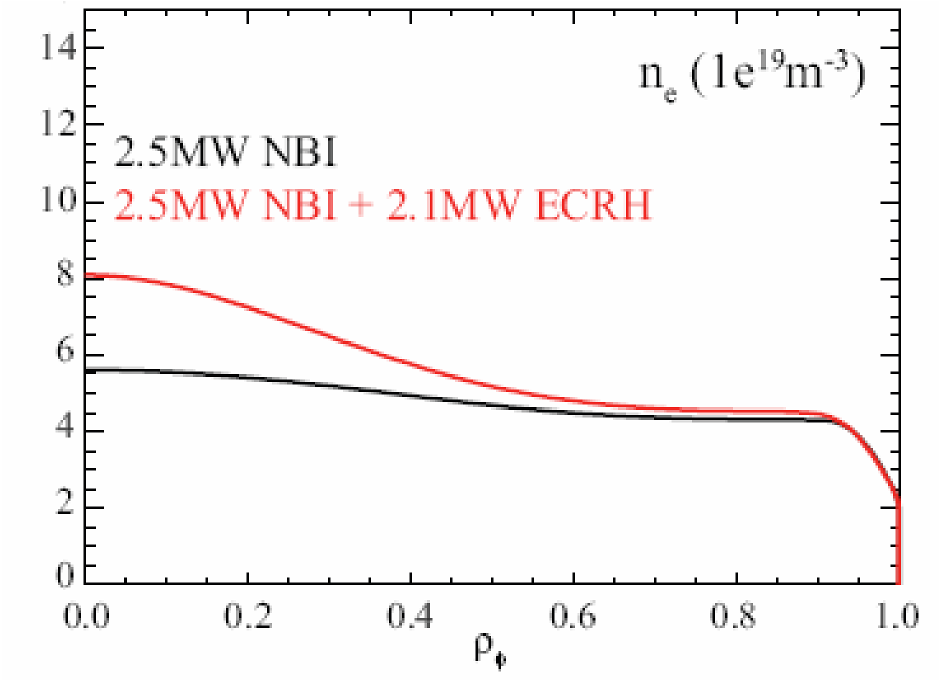


O2-mode allows heating (140 GHz, 2.5 T) at densities $n_e > 1.2\ 10^{20}\ m^{-3}$

ECRH used for dedicated transport studies (here: low I_p)

Central ECRH causes $T_e >> T_i$, low central rotation and n_e peaking





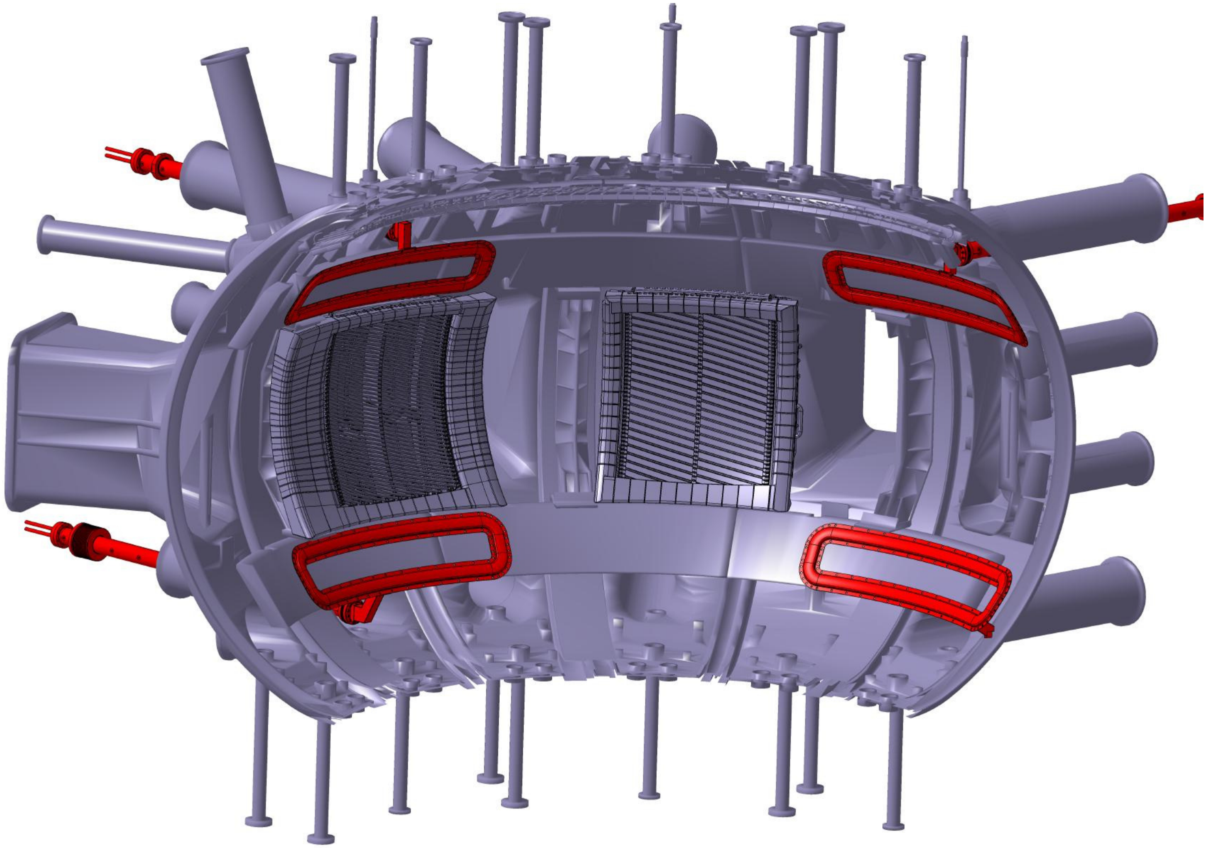
Explanation by theory (GS2, GYRO):
Central ECRH drives plasma towards more TEM dominated regime

⇒ Further upgrade ECRH III: 4 gyrotrons 0.5 MW, 2 s → 1 MW, 10 s, 2-f

Magnetic perturbation experiments for ELM mitigation

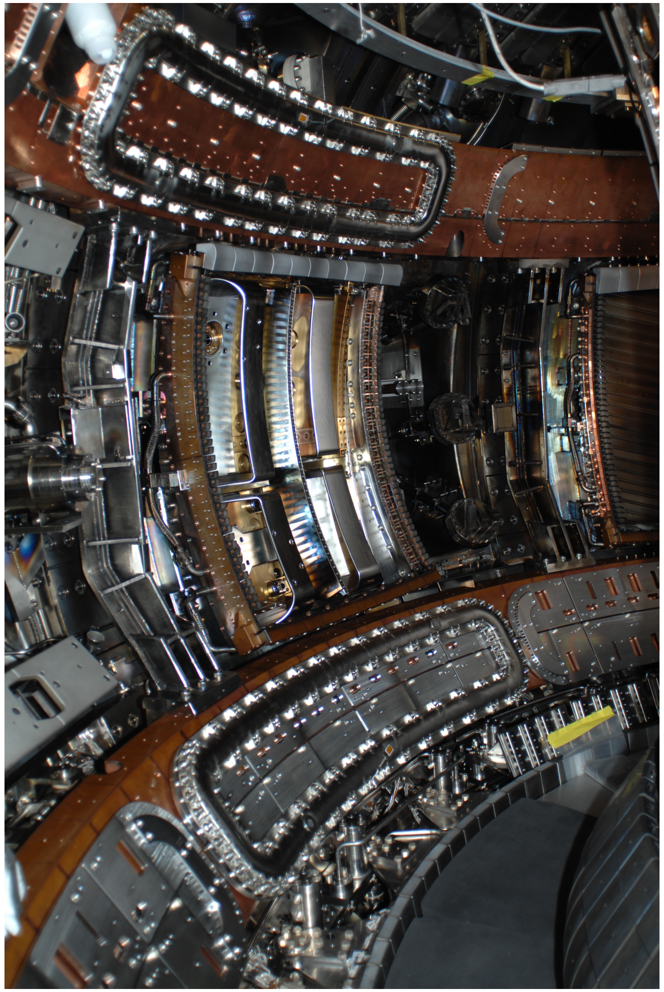
- ELM mitigation achieved above a critical density with n=2, resonant+non-resonant

First ELM mitigation experiments with B-coils



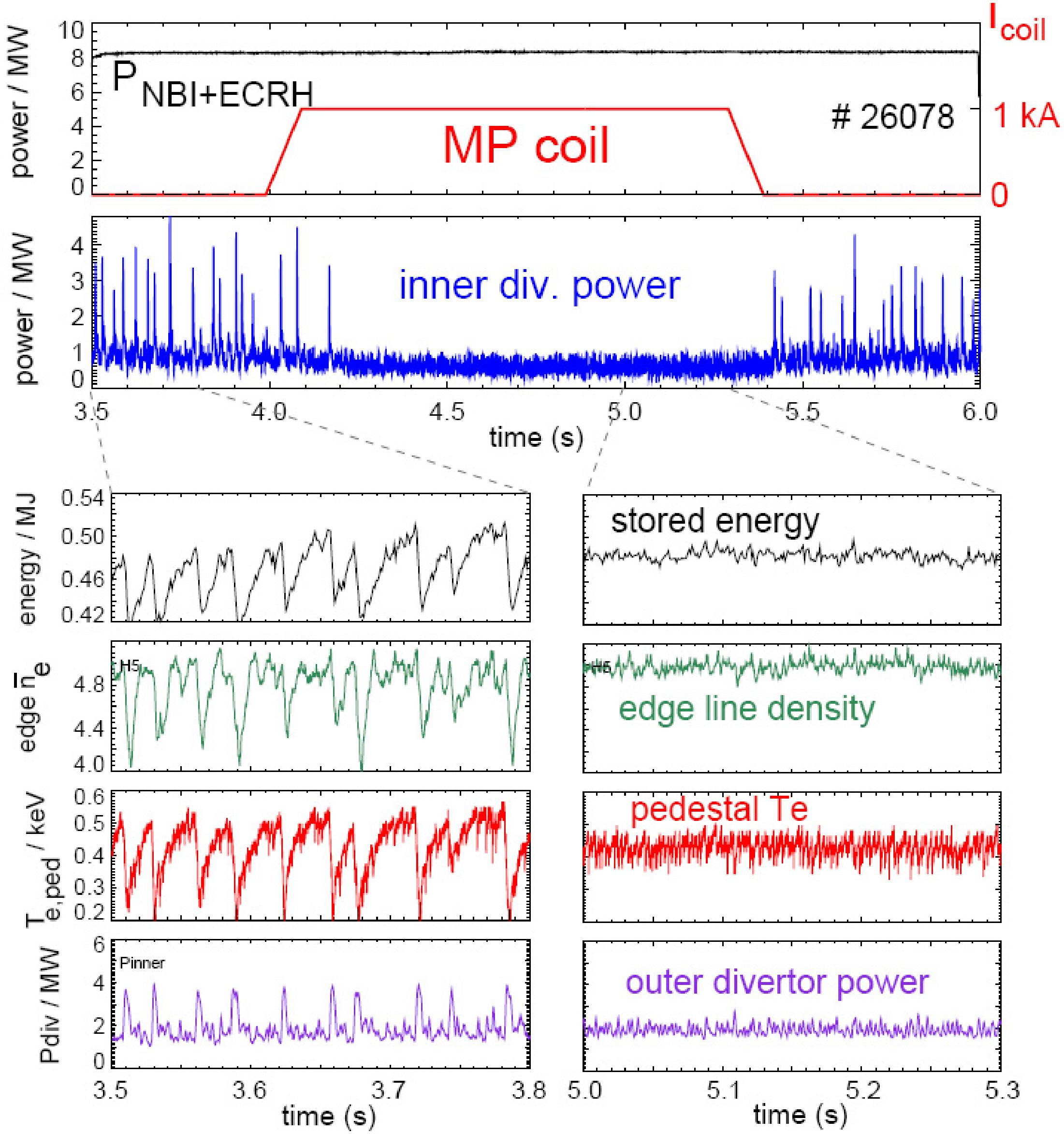
900 A ⊗ 5 windings

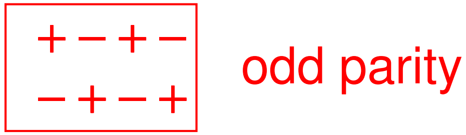
Magnetic pertubation coils are mounted close to the plasma



B-coil mounting, summer 2010

Comparison of type-I ELMy and ELM mitigated phases





ELM mitigation at high density
- ELMs turn to small, periodic events

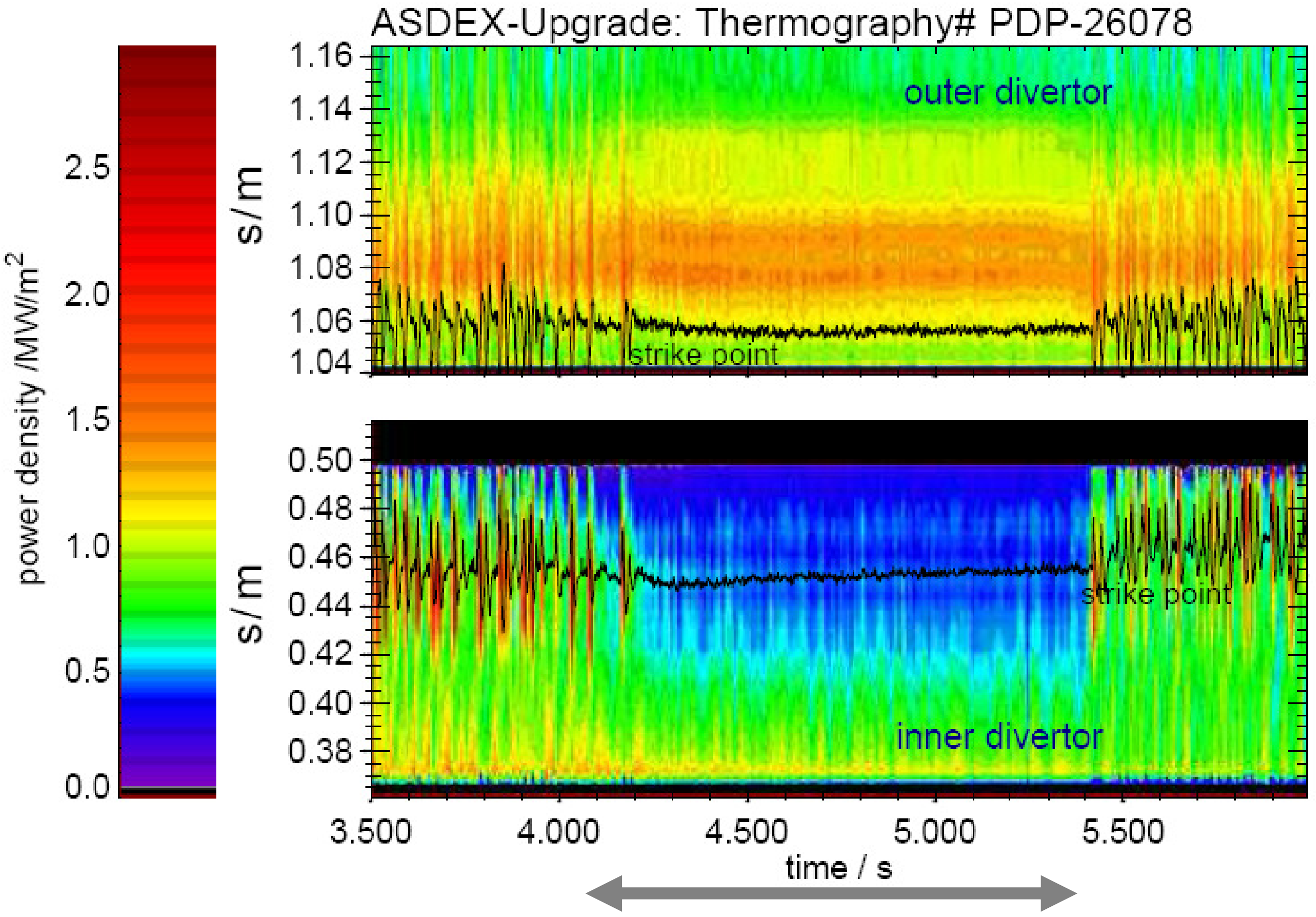
Independent of MP configuration

no density or energy pumpout in standard H-mode

W content does not rise

Power load from IR thermograpy (at one toroidal location)

- strongly reduced ELM load
- moderately increased inter-ELM load in outer divertor



outer divertor

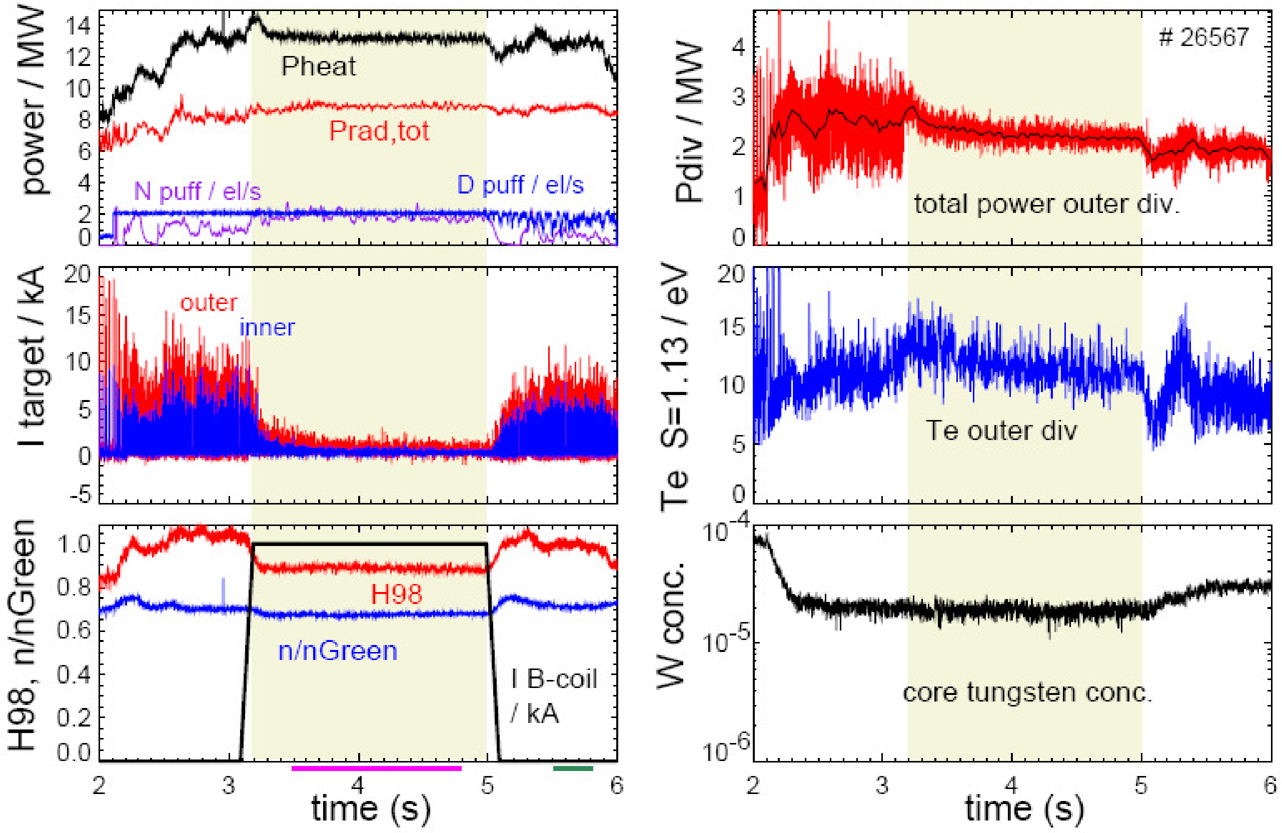
strike point splitting

inner divertor

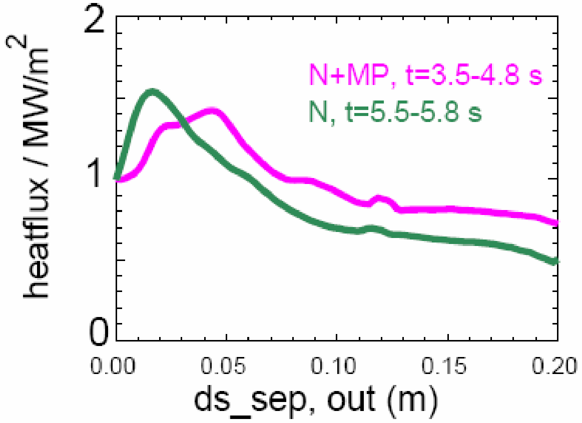
Coils on

Combination of MP ELM mitigation and nitrogen seeding

- very small ELMs, and benign divertor heat load
- confinement improvement due to nitrogen reverted by MP operation (still $H_{98}=0.9$)

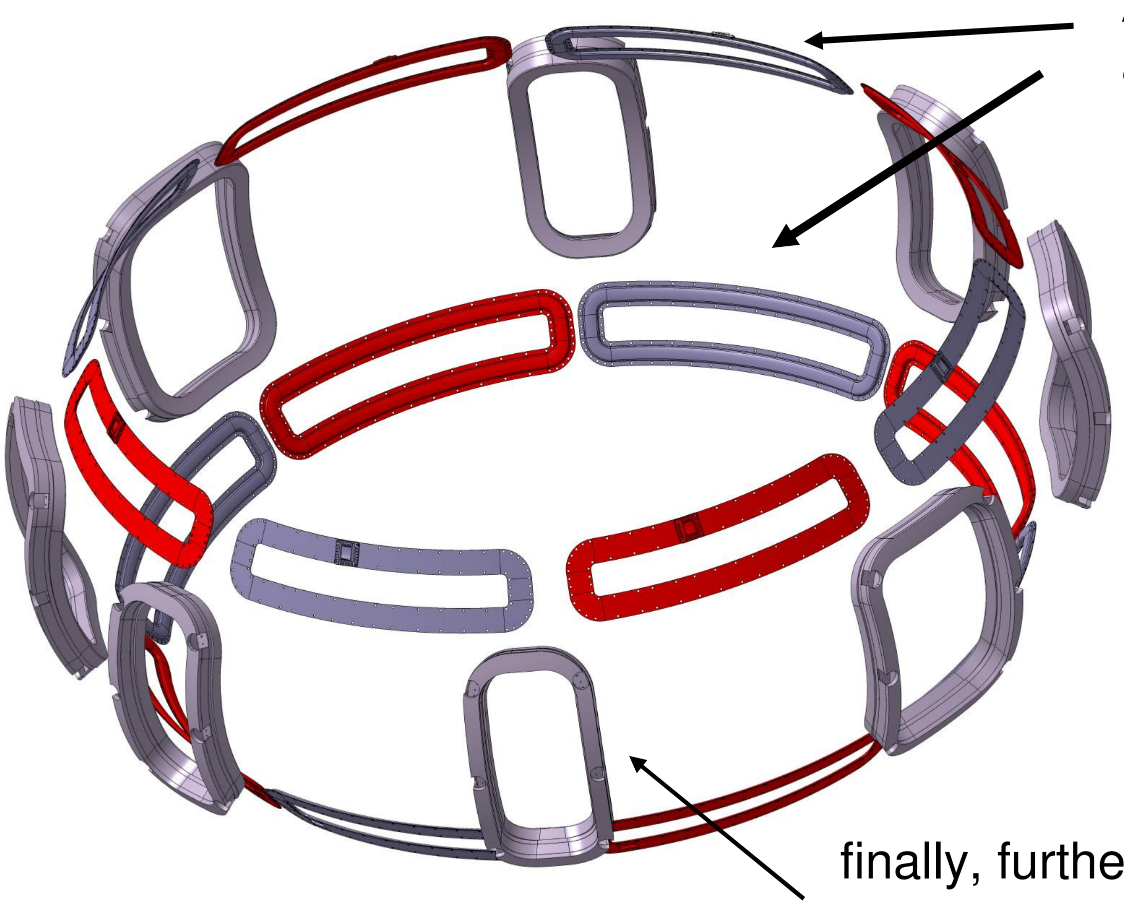


Peak heatflux < 1.5 MW/m^2 with 14 MW heating



effect of MPs on (seeded) plasma not yet understood →

Future extension of magnetic perturbation coils



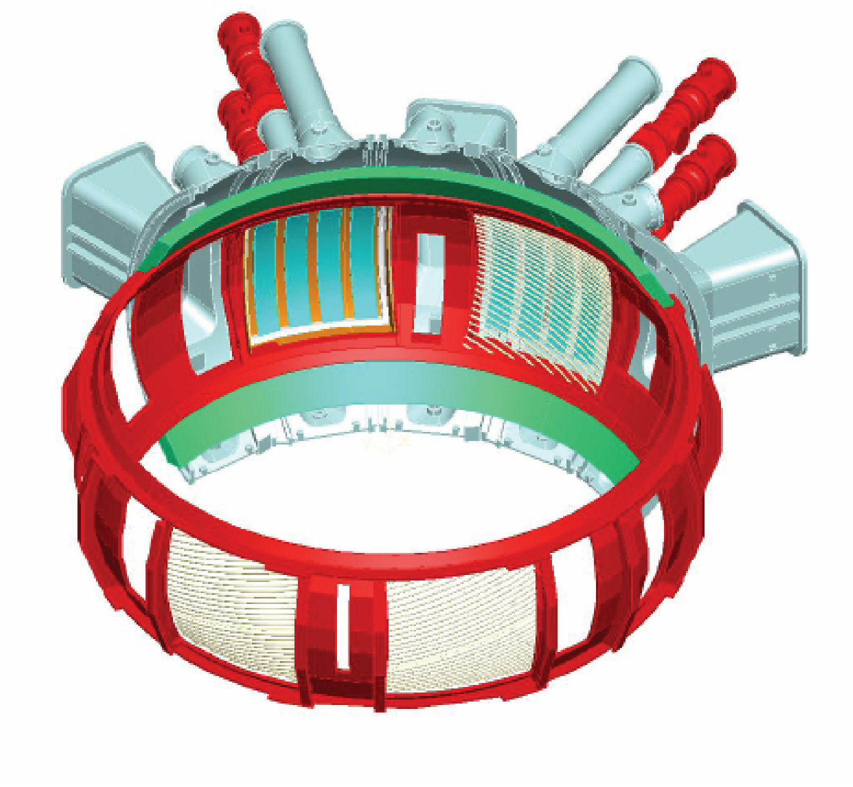
Aug-Dec 2011:
adding another 8 B-coils

finally, further 8 ‘A-coils’ will be
mounted in the midplane (2014/15)

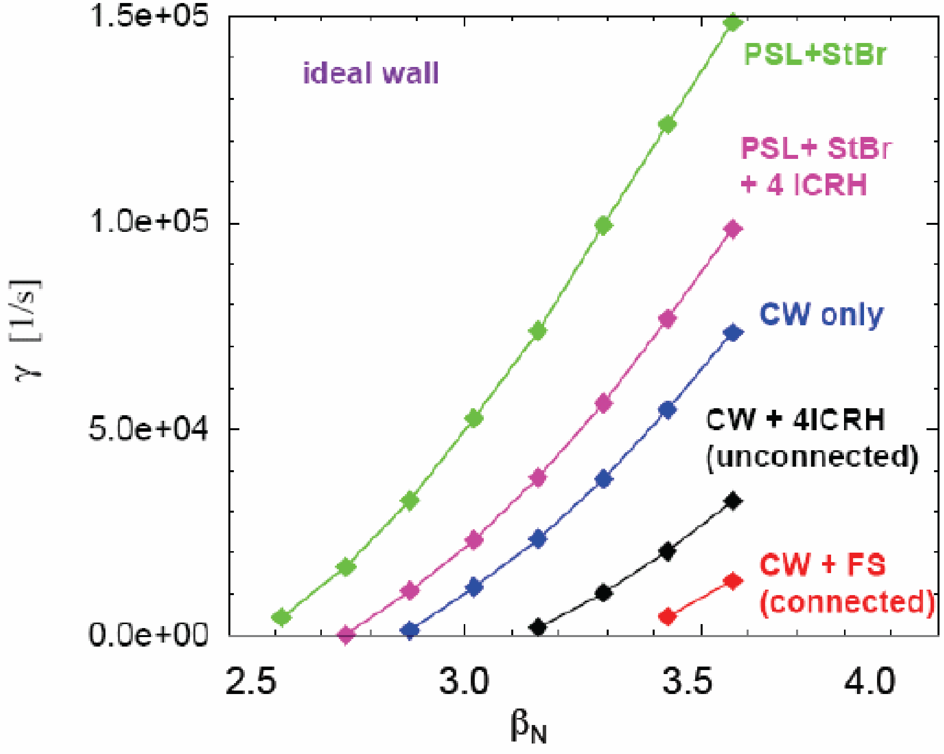
AC power supplies will allow to **rotate** the magnetic perturbations (e.g., for RWM stab.)
B-coils ~ 800 Hz, A-coils ~ 3 kHz

Final mid-term extension: a conductiong wall

- integrates improved ICRF antennas
- facilitates improved j(r) control capabilities

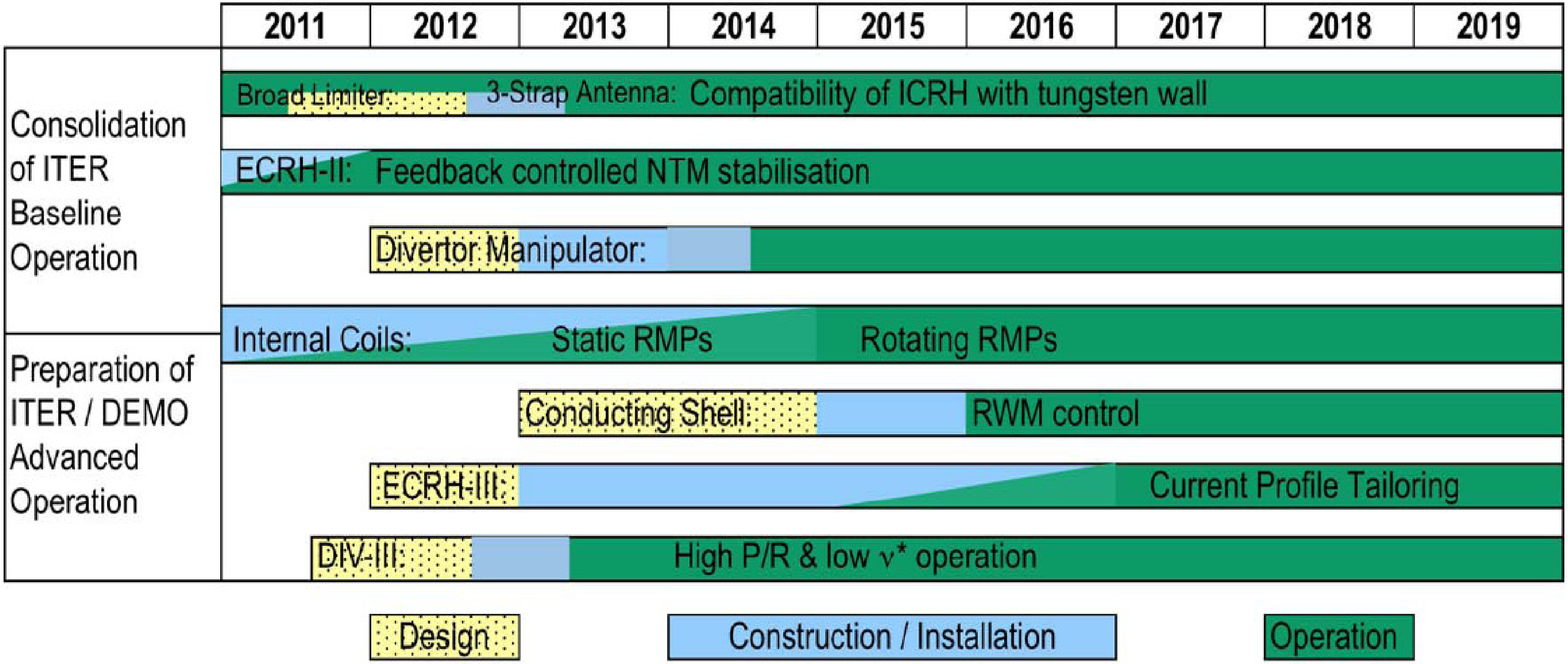


RWM growth rates



with active control, RWM stability increased by 50 % in advanced scenarios

ASDEX Upgrade future extensions – time plan



Schedule also determined by financial resources

Summary

- ASDEX Upgrade extensions allow to proceed the development of improved operating scenarios for ITER and DEMO

  + full W divertor, ICRF compatible to high-Z, ECRH upgrade, MP coils

- Full tungsten wall coverage ensures favourable exhaust conditions (while hampering use of internal barriers and very low ν^* in the core)

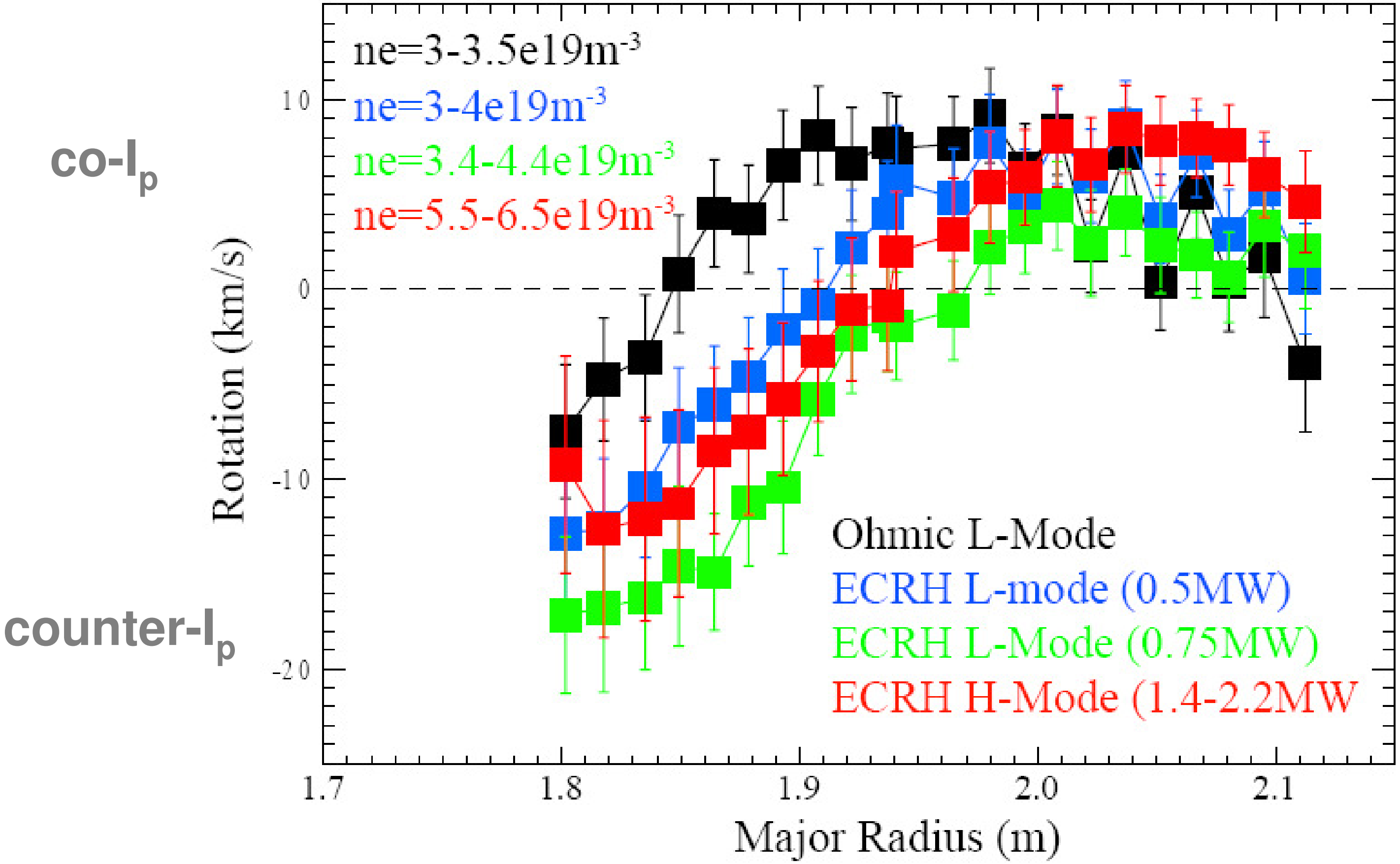
- diagnostic extensions ongoing for physics studies an strong theory support

- real-time diagnostics and active control are steadily increasing

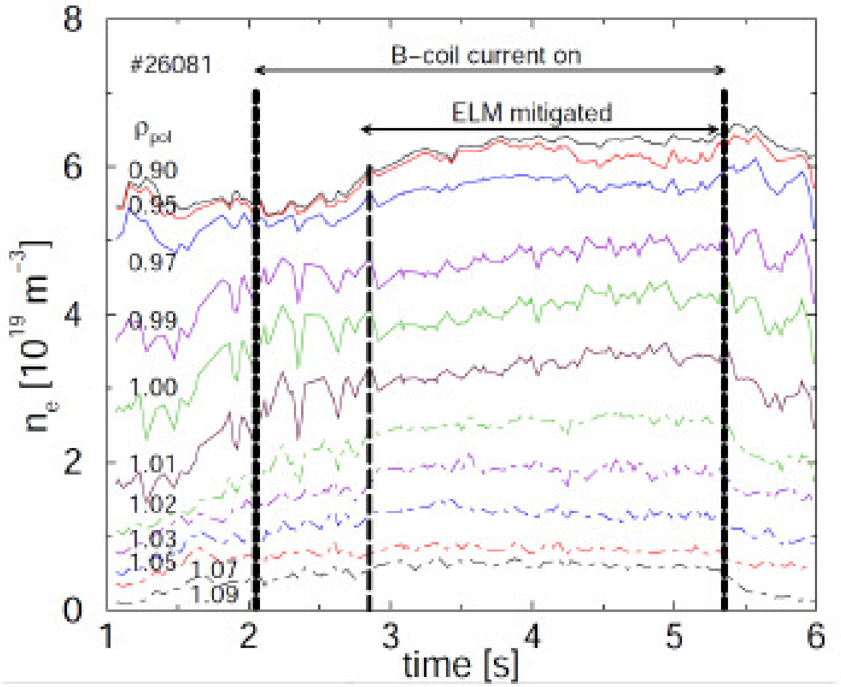
Reserve slides

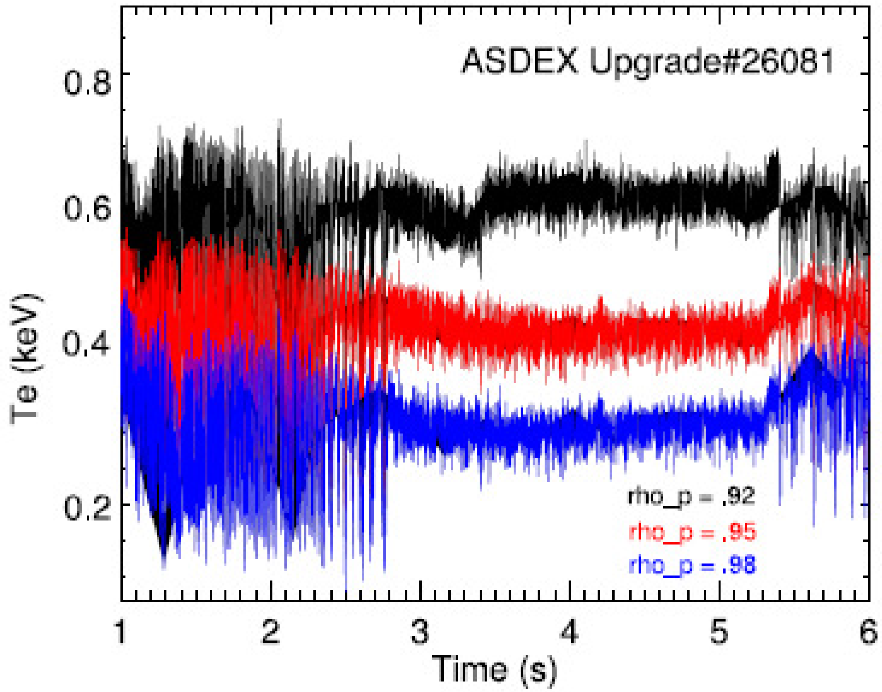
ECRH used for intrinsic rotation studies w/o external momentum input

Intrinsic AUG rotation counter-current in center, co-current in the edge
- goes more negative with heating power in L-mode
- H-mode brings positive offset velocity



Pedestal n_e, T_e profiles usually weakly affected by MP

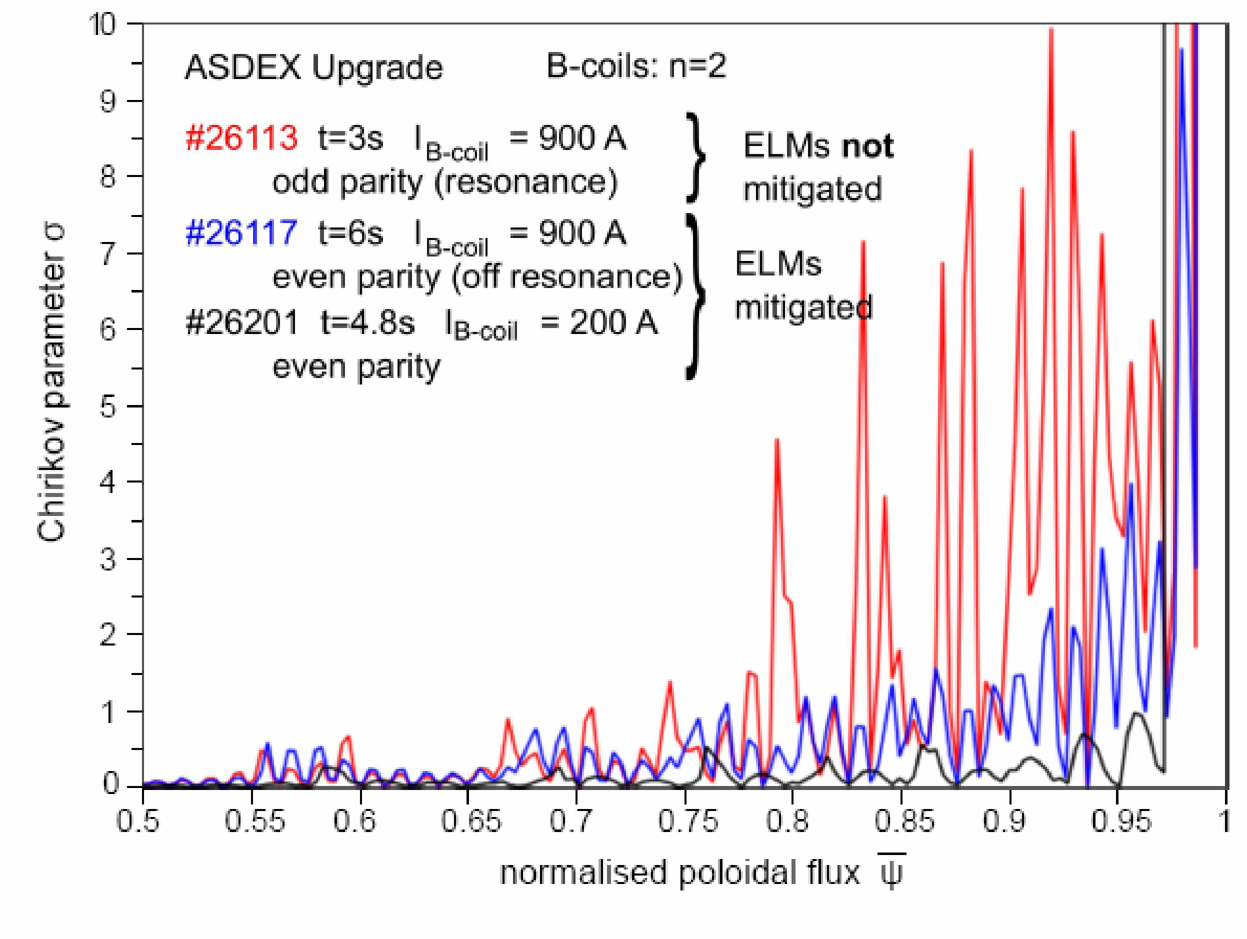




slight rise of pedestal density after coils are switched on
main effect on T_e is absence of large ELM drops

Mechanism of ELM mitigation so far not understood – extension of coils system

Chirikov parameter ("vacuum approximation")
- Large values obtained, but does not predict ELM mitigation



ELMs mitigated with both "resonant" (odd) and "non-resonant" (even) configurations.