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Rotation induced by ICR heating in the tokamak TEXTOR

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Motivation

- ✓ *In fusion reactor, NBI is expected to be unable to drive the plasma rotation much.*
- ✓ *Slow rotation can lead to enhanced turbulence transport and decreased stability of MHD modes => confinement deterioration.*
- ✓ *Will be a plasma intrinsic rotation enough for the next generation of fusion devices?*
- ✓ *On many fusion machines there were reported the observations that the ICRH waves launched to the plasma are often accompanied by the change in the plasma rotation. [see M.F.Nave O4.122, Y.Lin P5.164 & J.Rice P5.181 EPS2010]*
- ✓ *The necessity of further understanding of the physics underlying this effect motivates the dedicated study on TEXTOR.*

Outline

- Scheme of Experiment
- Experimental Results

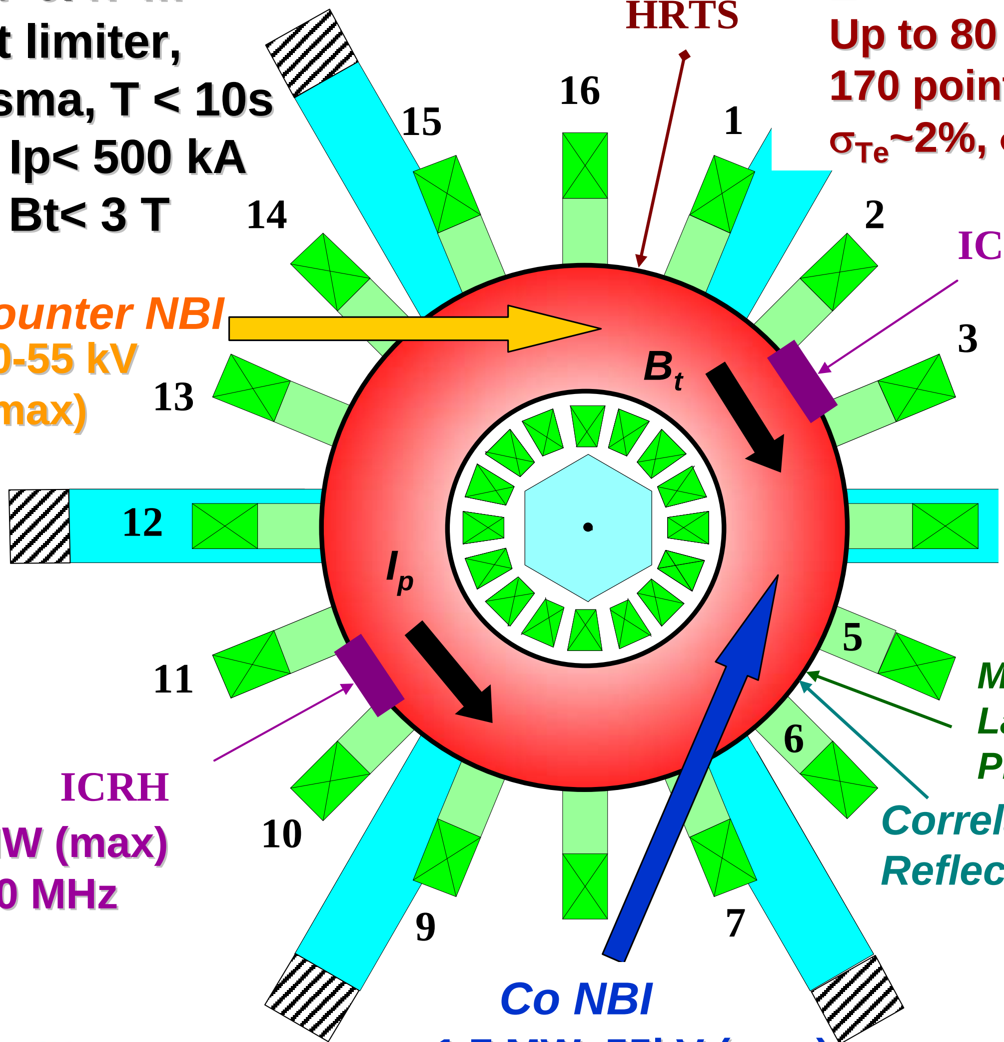
  - Scenario I (Ip=200 kA, Bt=1.9 T, a weak NBI)

  - Scenario II (Ip=400 kA, Bt=2.5 T, 0<PNBI<1MW)
- Discussion
- Conclusions

TEXTOR

R_0=1.75 m, a=0.47 m
Toroidal belt limiter,
Circular plasma, T < 10s
Ip< 500 kA
Bt< 3 T

Δt=200 us , $T_e(Z)$, $n_e(Z)$
Up to 80 profiles per discharge
170 points per profile
σ_{Te}~2%, σ_{ne}~1%



Counter NBI
Uacc = 50-55 kV
1.7 MW (max)

Charge eXchange Recombination Spectroscopy (on NBI-co)
Ω_φ, T_i
ΔR~2-3 cm, Δt~40 ms

Movable Langmuir Probe

ICRH
2 x 2 MW (max)
25<f<40 MHz

Correlation Reflectometer
$\tilde{n}_e(t)$, $\Omega_\perp^{turb}$
t_{ADC} =0.5 us ,
0< $k_\perp$< 4 cm^{-1}

Co NBI
1.7 MW, 55kV (max)

Scenario I

target plasma

$Ip=200$ kA, $Bt=1.9$ T, $qa=5.3$

$P_{NBI-Co}=$ 0.3 MW

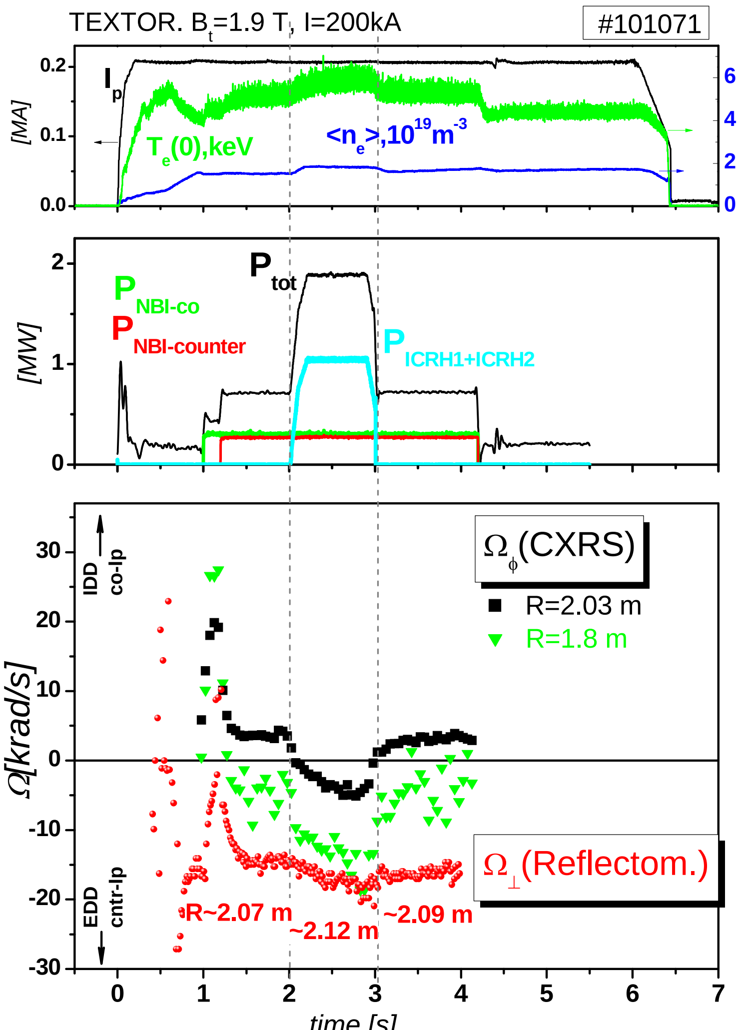
$P_{NBI-Counter}=0.3$ MW

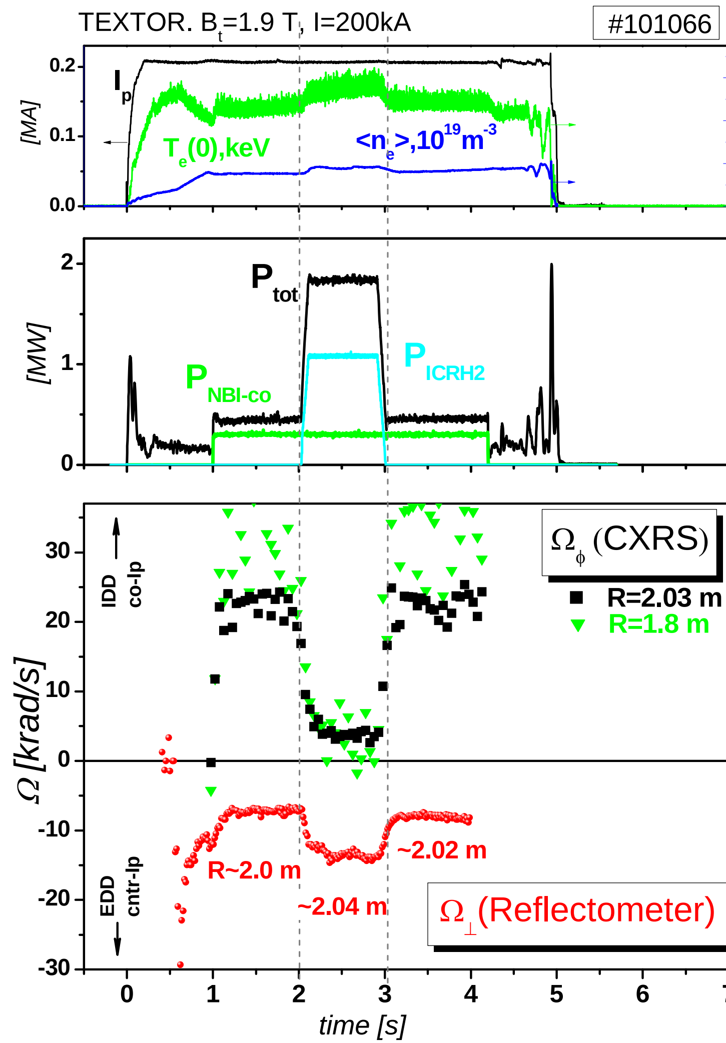
ICRH

$f_{ICRH}=29MHz$

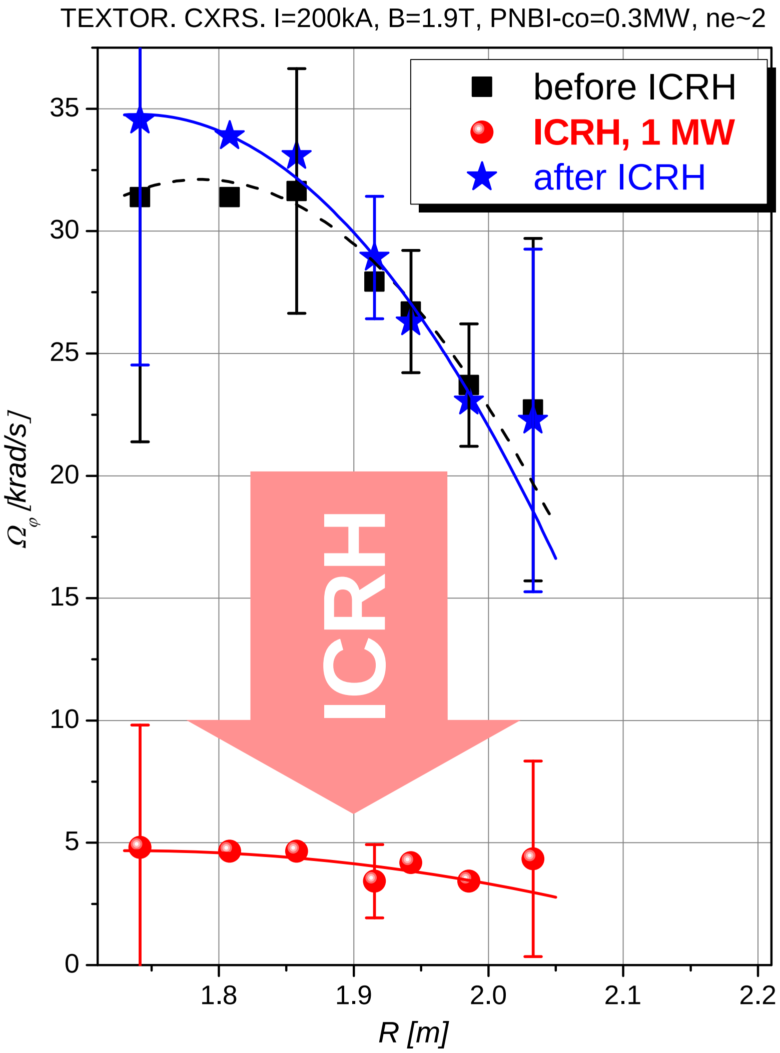
$0<P_{ICRH}<1.5$ MW

#101071 vs #101066



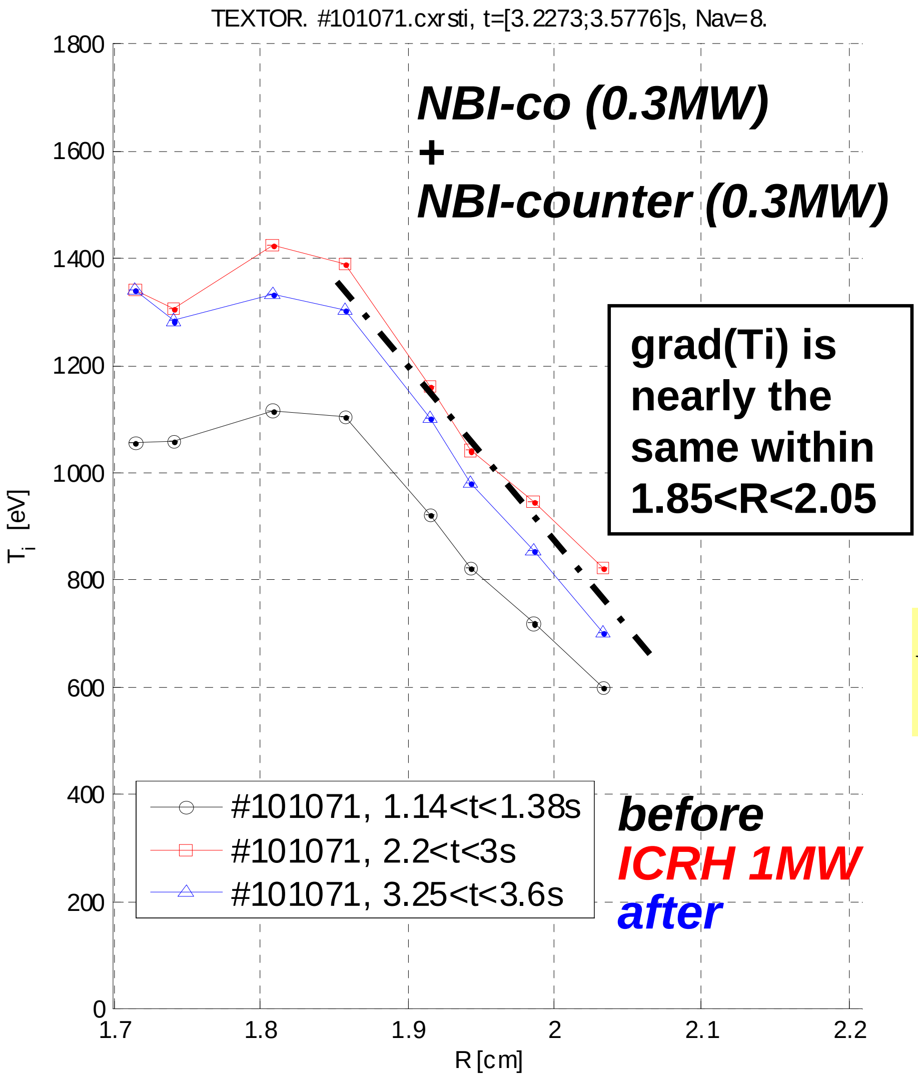


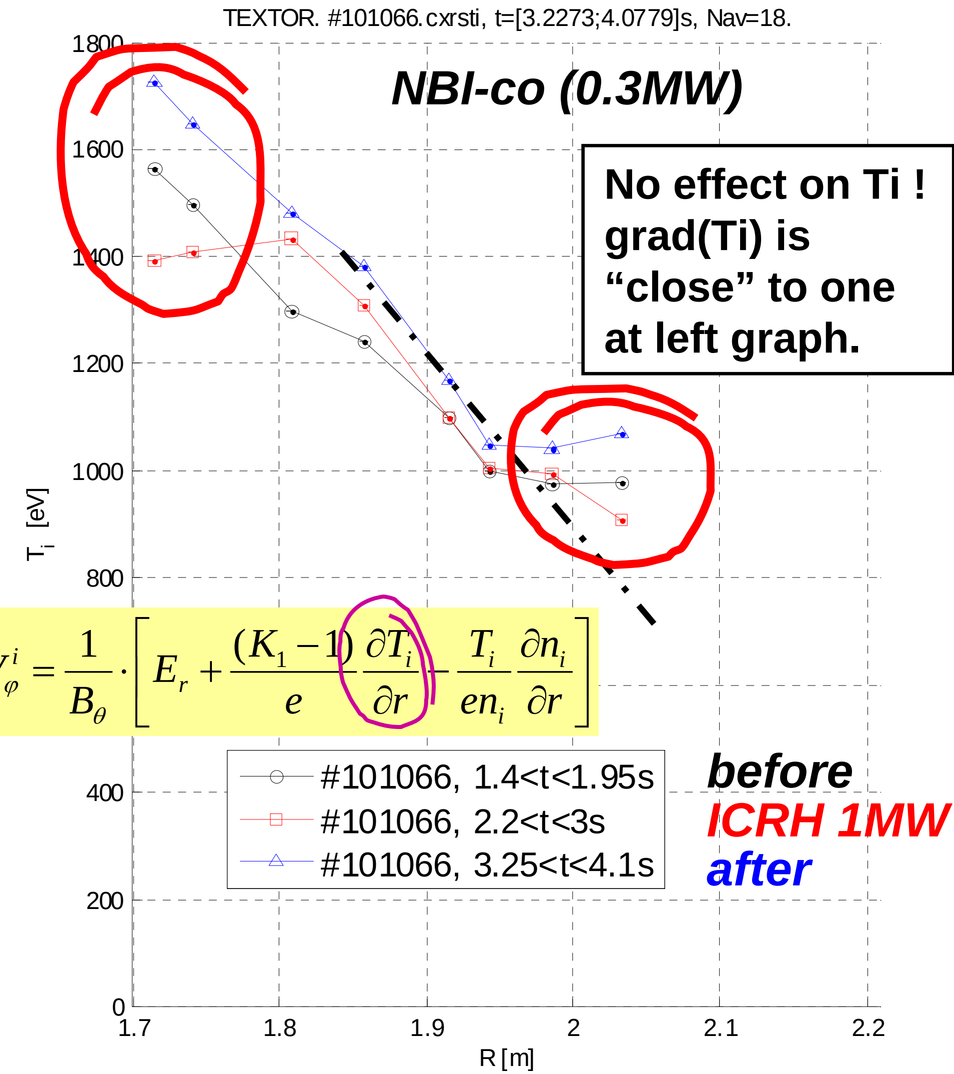
#101071 vs #101066



#101066 vs #101071

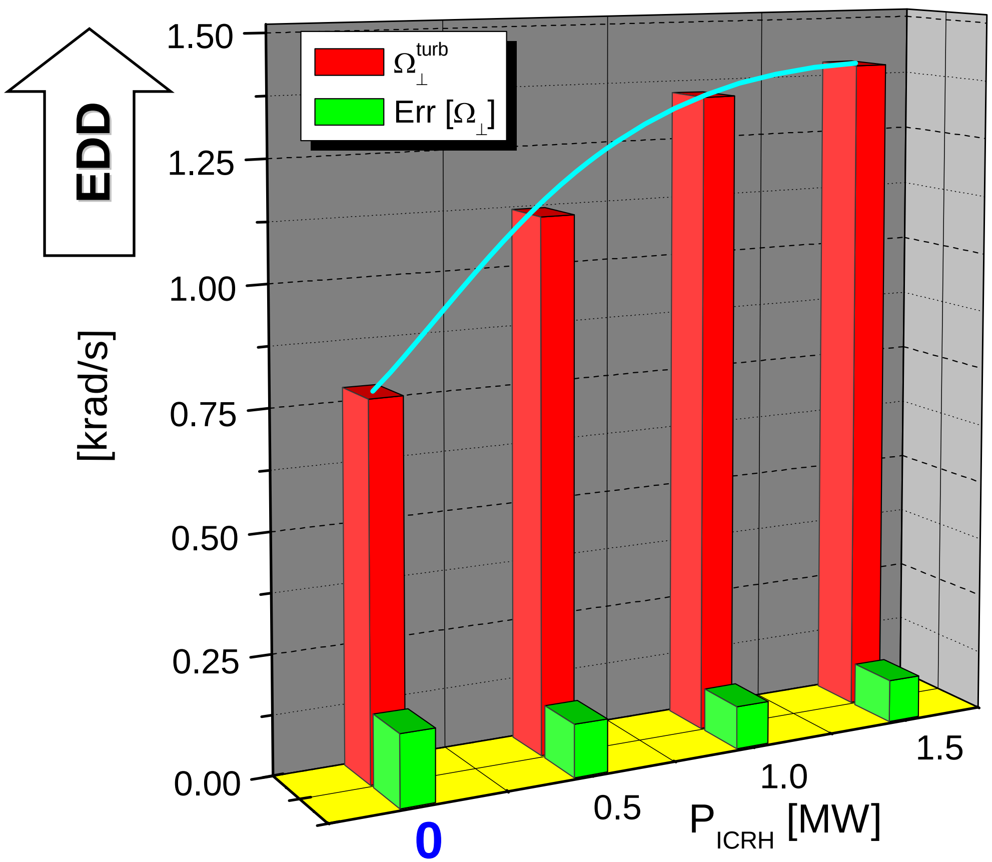
I_p=200 kA , B_t=1.9 T





$$V_\varphi^i = \frac{1}{B_\theta}\cdot\left[E_r + \frac{(K_1-1)}{e}\frac{\partial T_i}{\partial r} - \frac{T_i}{en_i}\frac{\partial n_i}{\partial r}\right]$$

Power dependence, $\Omega_\perp$



✓ ***Effect increases with PICRH though indicating some nonlinear saturation.***

Scenario II

target plasma:

Ip=400 kA, Bt=2.5 T, qa=3.9

$0 < P_{NBI\text{-}Co} < 0.9$ MW

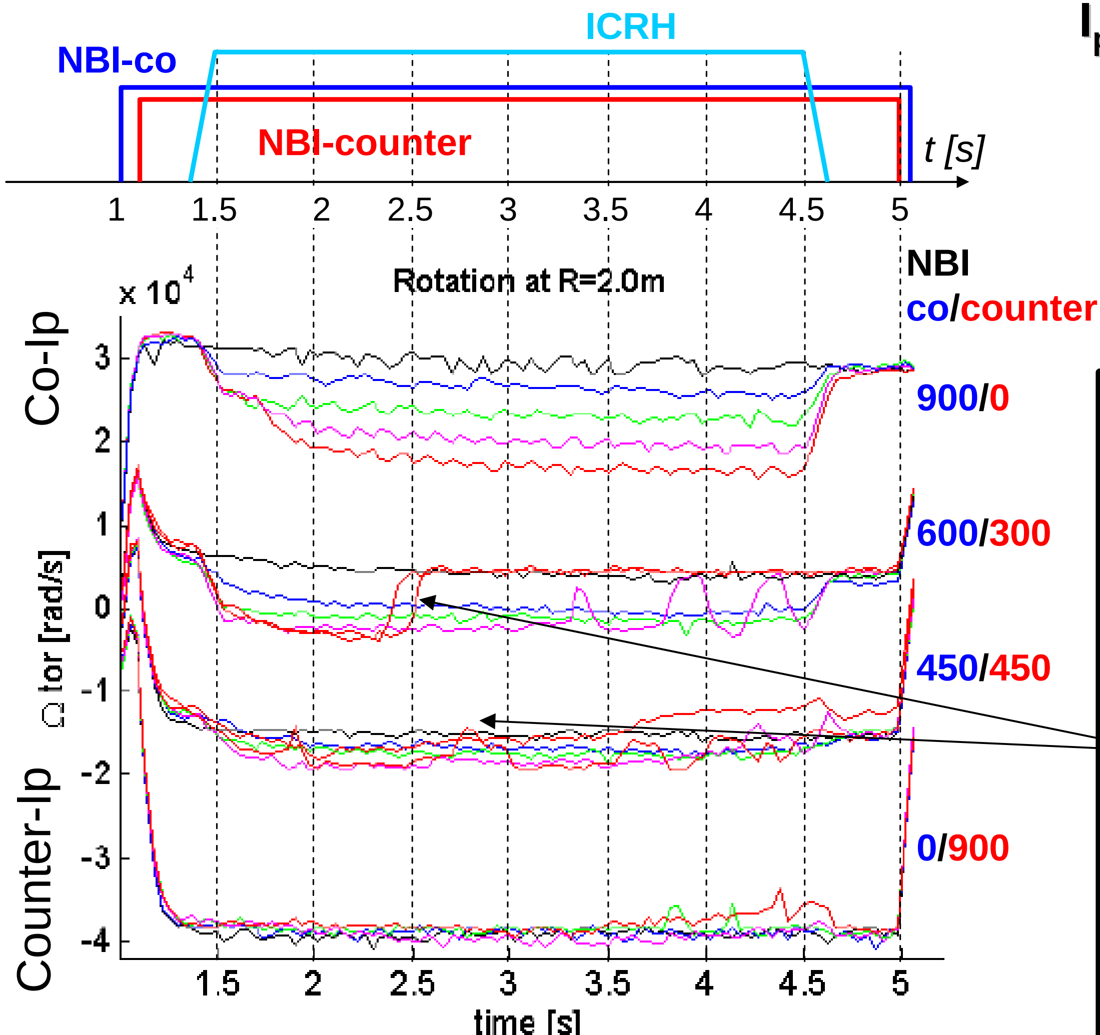
$0 < P_{NBI\text{-}Counter} < 0.9$ MW

ICRH

$f_{ICRH} = 38$MHz

$0 < P_{ICRH} < 1$ MW

Toroidal rotation



I_p=400 kA , B_t=2.5 T, f_{ICRH}=38MHz

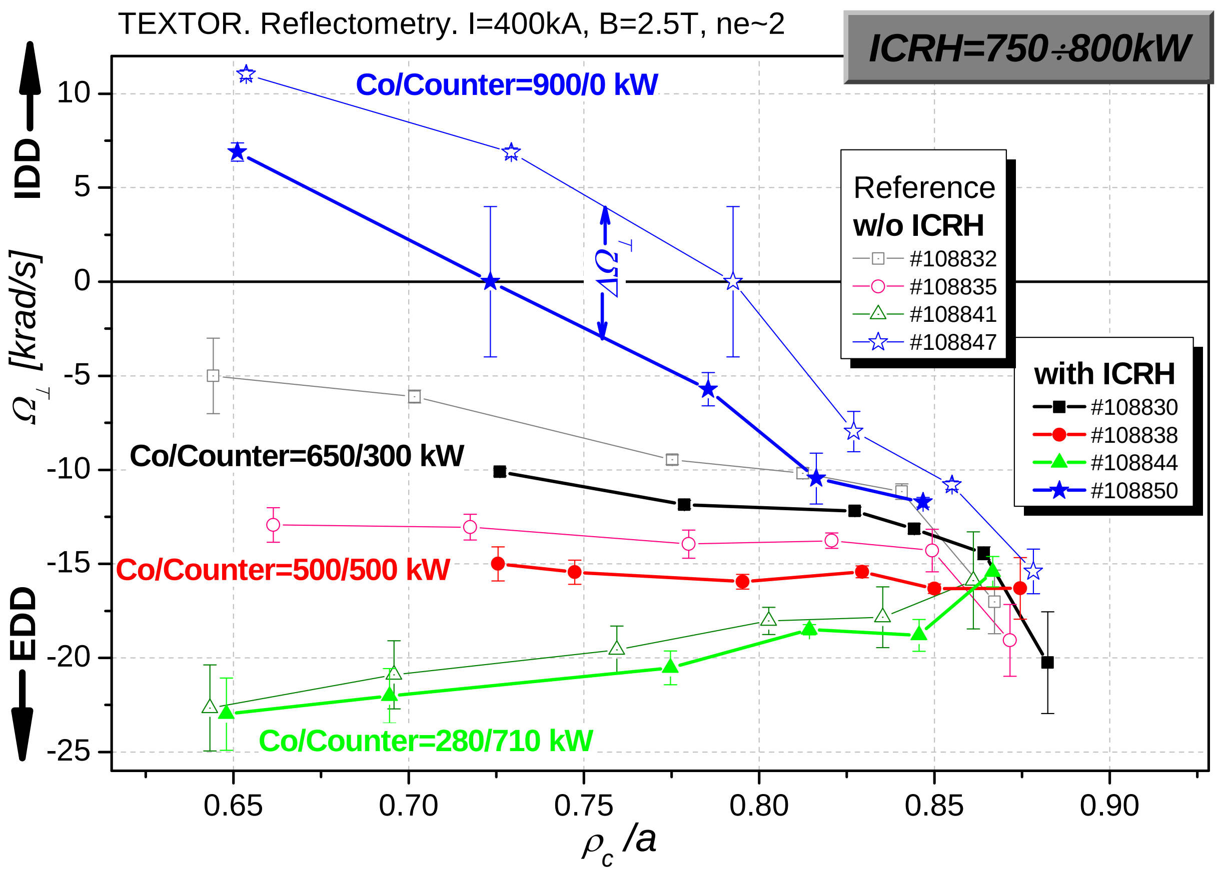
Color code:

black: no ICRH
blue: 200-500 kW
green: 500-800 kW
magenta: 800-1100 kW
red: >1100 kW

- ✓ ***A clear decrease of the effect with***
  $$P_{NBI}^{co} \Big/ \left(P_{NBI}^{co} + P_{NBI}^{counter} \right)$$
- ✓ ***Some deviations in Ω(t) traces are due to the ICRH power breakdowns.***
- ✓ ***Velocity decays with a char. times of ~100ms, comparable with τ_e~50ms for these plasmas. [agrees with C-Mod , J.Rice NF 1999]***

Turbulence rotation, $\Omega_\perp$

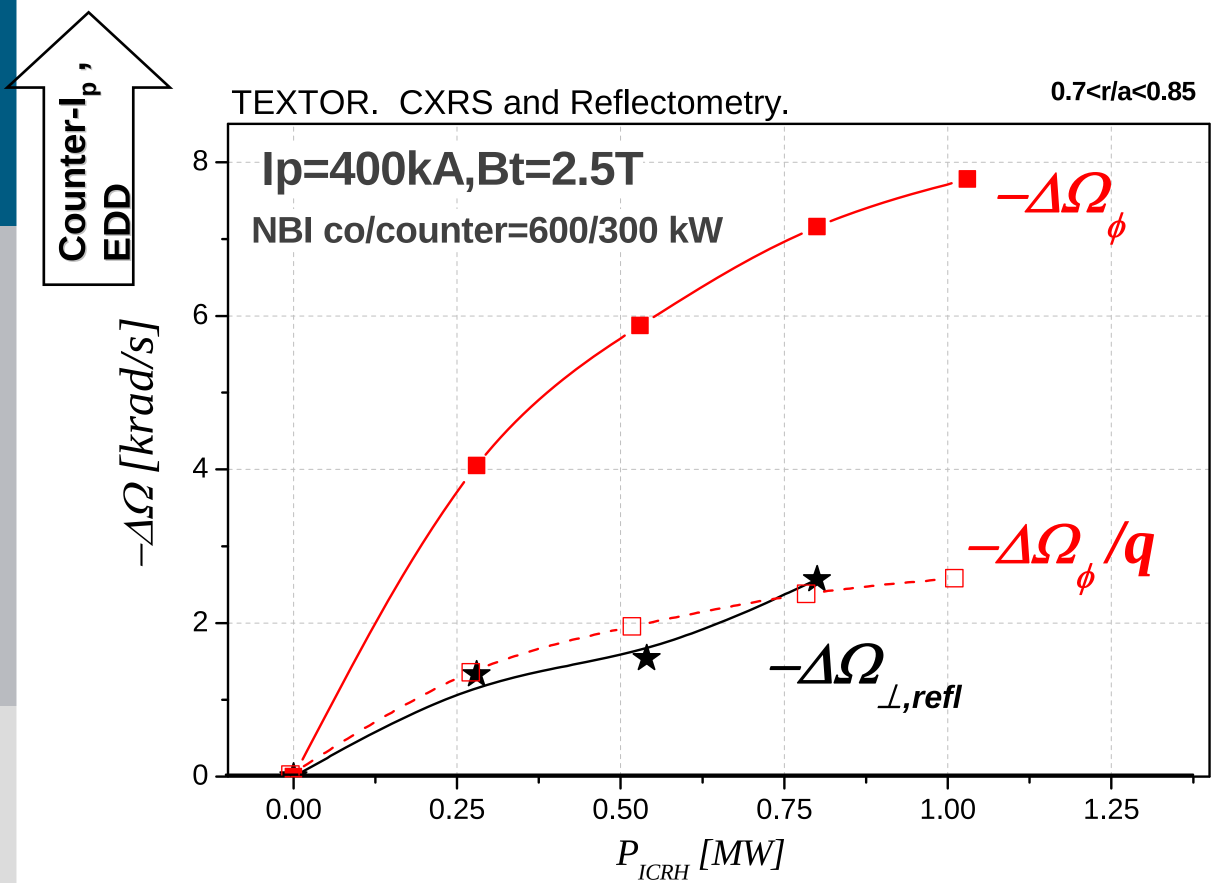
I_p=400 kA , B_t=2.5 T



- ✓ $\Omega_\perp$ **follows the projection of** Ω^{pl}_φ **to to** $\perp B$ **direction**
- ✓ ***Effect reduces with decrease of*** $P^{co}_{NBI} / \left(P^{co}_{NBI} + P^{counter}_{NBI}\right)$
- ✓ ***Peripheral rotation is nearly not influenced neither by ICRH nor NBI !***

$$\Omega_{refl} = \Omega^{pl}_{\perp} + \Omega_{turb} = \Omega^{pl}_{\theta} - \Omega^{pl}_{\varphi}/q + \Omega_{turb}$$

Power dependence. $\Omega_\perp$ vs Ω_φ



- ✓ ***Effect increases with P_{ICRH} though indicating some nonlinear saturation.***
- ✓ $\Delta\Omega^{refl}_\perp \sim \Delta\Omega_\varphi/q$ =>

  1) *variation of turbulence propagation in palsma frame is compensated by poloidal rotation excursion* $\Delta\Omega_{turb} \approx -\Delta\Omega^{pl}_\theta$

  or

  2) $|\Omega_{turb}| \sim |\Omega^{pl}_\theta| << \Omega^{pl}_\varphi/q$

$$\Omega_{refl} = \Omega^{pl}_\perp + \Omega_{turb} = \Omega^{pl}_\theta - \Omega^{pl}_\varphi/q + \Omega_{turb}$$

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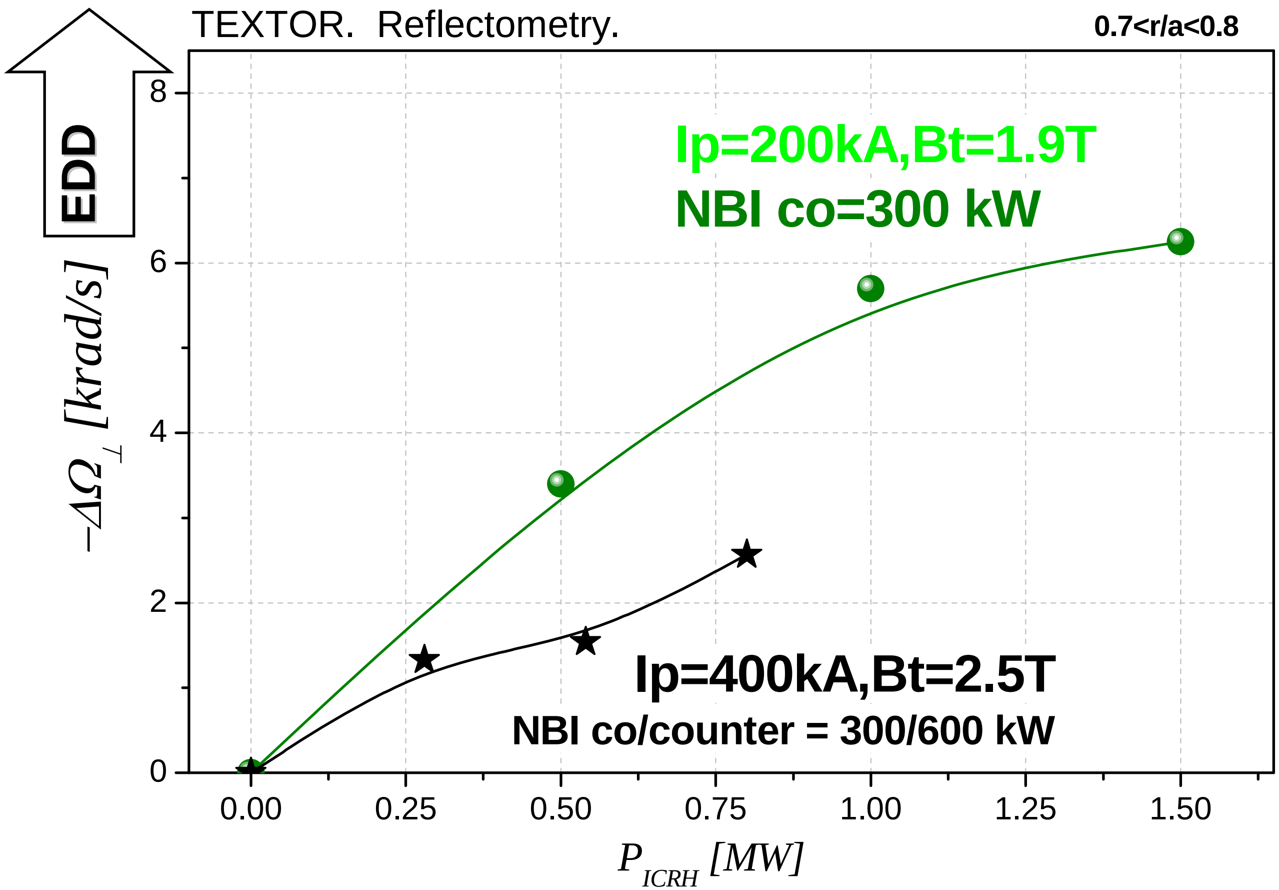
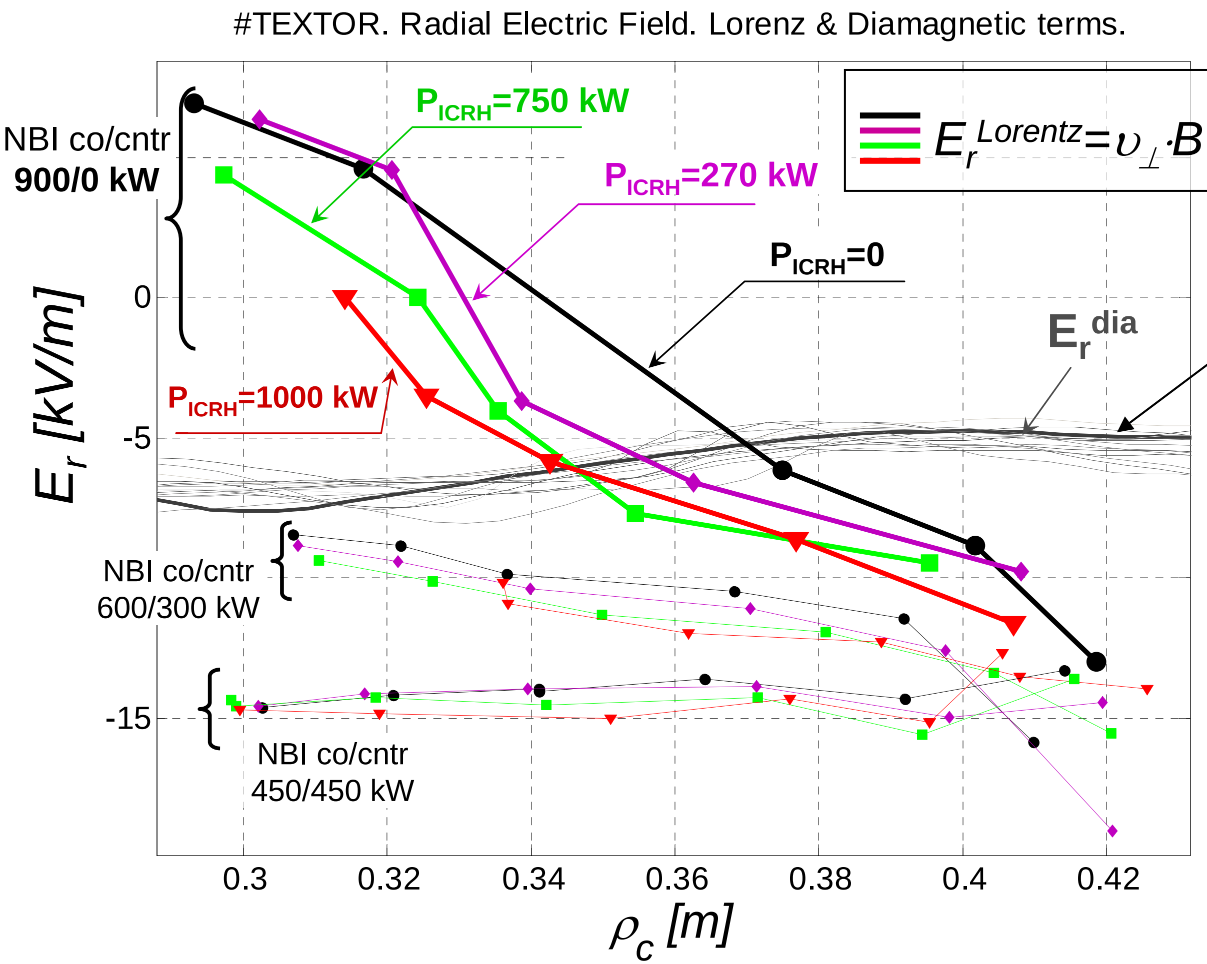
Power dependence: Higher fields vs lower



✓ *The trends are the same, but the effect is higher for Ip/Bt=200kA/1.9T scenario as compared with Ip/Bt=400kA/2.5T.*

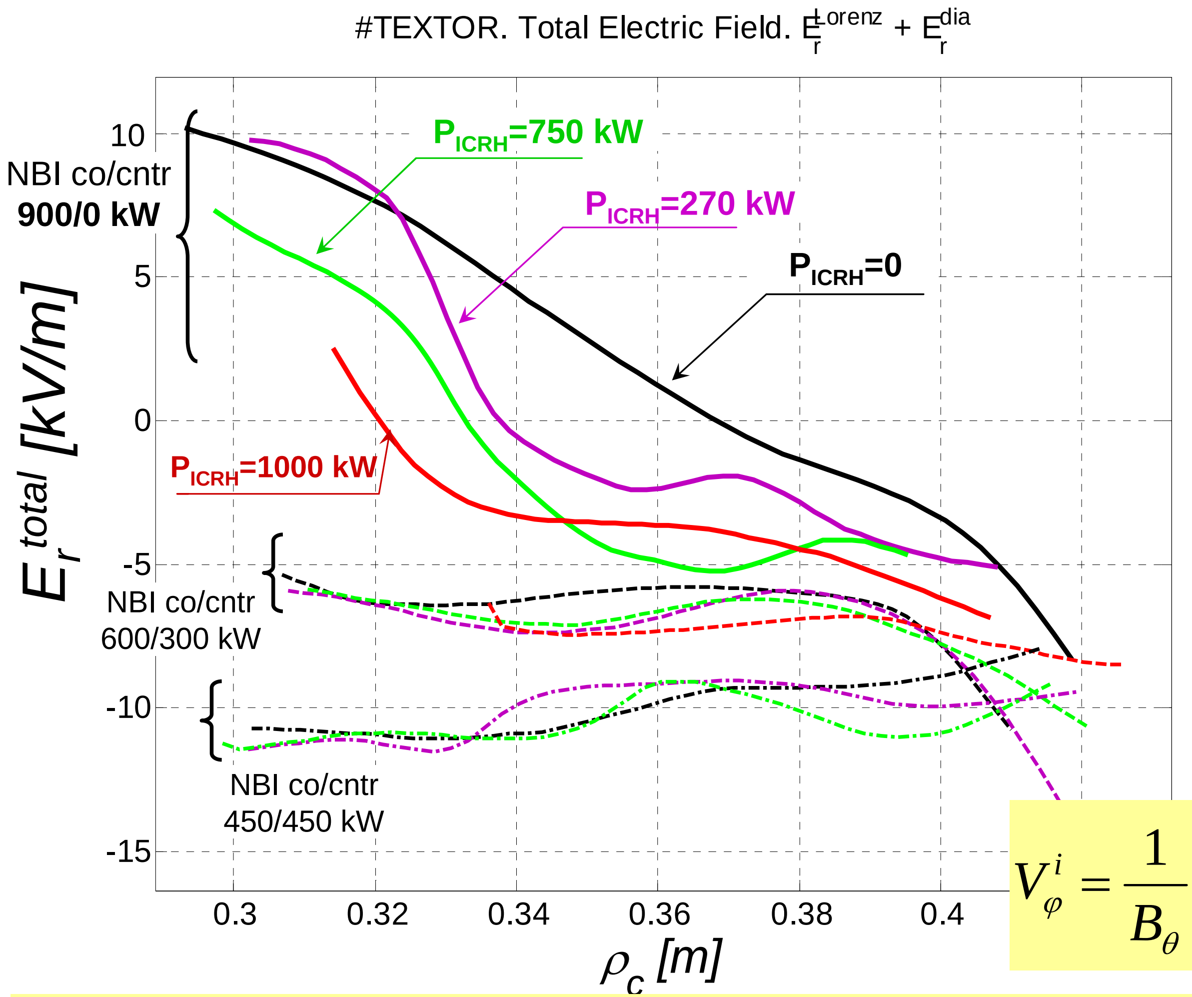
$$E_r = \frac{\nabla p_i}{Z_i e n_i} + \upsilon_\perp B = E_r^{dia} + E_r^{Lorentz}$$



- ✓ ***The diamagnetic term is not much influenced by neither ICRH nor P_{NBI-co}/ $P_{NBI-counter}$ ratio** (for all scenarios shown in gray scale).*
- ✓ ***Variations in the Lorentz term are maximal for the highest P_{NBI-co}/ $P_{NBI-counter}$ ratio and increase with P_{ICRH}.***

Total Er

$$E_r = \frac{\nabla p_i}{Z_i e n_i} + \upsilon_\perp B = E_r^{dia} + E_r^{Lorentz}$$



- ✓ ***Radial electric field decreases in the region 0.3<r<0.4 m (0.65<r/a<0.85) by -8<ΔE$_r$<-3 kV/m after ICRH is applied.***
- ✓ ***For $P_{ICRH} \approx 300$ kW, E_r deepens almost locally within ~5 cm centering at r/a~0.75. When increasing P_{ICRH} E_r well deepens and broadens.***

$$V_\varphi^i = \frac{1}{B_\theta} \cdot \left[E_r + \frac{(K_1 - 1)}{e} \frac{\partial T_i}{\partial r} - \frac{T_i}{e n_i} \frac{\partial n_i}{\partial r} \right]$$

-8<ΔEr<-3 kV/m => $\Delta\Omega_\varphi \sim \Delta Er/B_\theta/R$ => 12< $\Delta\Omega_\varphi$<20 krad/s, that is somewhat higher compare to experiment 4< $\Delta\Omega_\varphi$<13 krad/s (see slide 10)

Discussion

	P_{ICRH}	
Alcator C-Mod *[J.E.Rice EPS2010 P5.181, J.E.Rice et al, NF2007, J.E.Rice et al, NF2001, J.E.Rice et al, NF1999]*	<4MW	***strong co-Ip rotation*** $\Delta\upsilon \sim P_{ICRH}^{1.3}\ Ip^{0.5}\ ne^{-1.0}\ f_{ICRH}^{-1.0}$
JET *[M.F.F. Nave et al, EPS2010, L-G Eriksson et al, NF2009]*	<4MW	***δ=0.08% => weak co- or counter-Ip rotation*** ***δ=1.5% => stronger counter-Ip rotation*** ***no dependencies on P_{ICRH} and β_n are found***
Tore Supra *G.T. Hoang et al, NF2000*	<9MW	***standard L-mode => counter-Ip rotation*** ***improved L-mode => co-Ip rotation***
TEXTOR *[S. Soldatov et al, EPS2010]*	<4MW	***strong counter-Ip rotation*** $\Delta\upsilon \sim P_{ICRH}$ $\Delta\upsilon \sim P_{coNBI}/(P_{counterNBI} + P_{coNBI})$

Conclusions

- *The application of ICRH leads to an acceleration of plasma rotation both in EDD and counter-Ip direction. Increasing scaling: $\Delta\upsilon \sim P_{ICRH}$*
- ***The effect depends on the toroidal rotation of target plasmas. The higher $P_{coNBI}/(P_{counterNBI} + P_{coNBI})$ ratio, the larger effect of the ICRH induced rotation.***
- *After ICRH application the radial electric field in the region 0.3<r<0.4 m (0.65<r/a<0.85) is found to decrease by $-8<\Delta E_r<-3$ kV/m depending on P_{ICRH}.*
- *The variations of $\Omega^{turb}_{\perp}$ and Ω_{φ} due to ICRH is applied are consistent in the sense $\Delta\,\Omega^{turb}_{\perp} \approx \Delta\,\Omega_{\varphi}/q$.*
- *The estimated $\Delta\upsilon_{\varphi} \sim \Delta E_r/B_{\theta}$ lies within 12-20 krad/s that agrees (though exceeding) by the order of magnitude with the experimental $4<\Delta\upsilon_{\varphi}<13$ krad/s.*
- *The effect is more pronounced for plasmas with Ip/Bt=200kA/1.9T as compared with Ip/Bt=400kA/2.5T that could be a consequence of either i) the difference in the MC mechanism which suppose to be sensitive to poloidal and toroidal fields in a tokamak or ii) simply NC effect $\Delta\upsilon_{\varphi} \sim 1/B_{\theta}$ (reported also by J.Rice et al).*