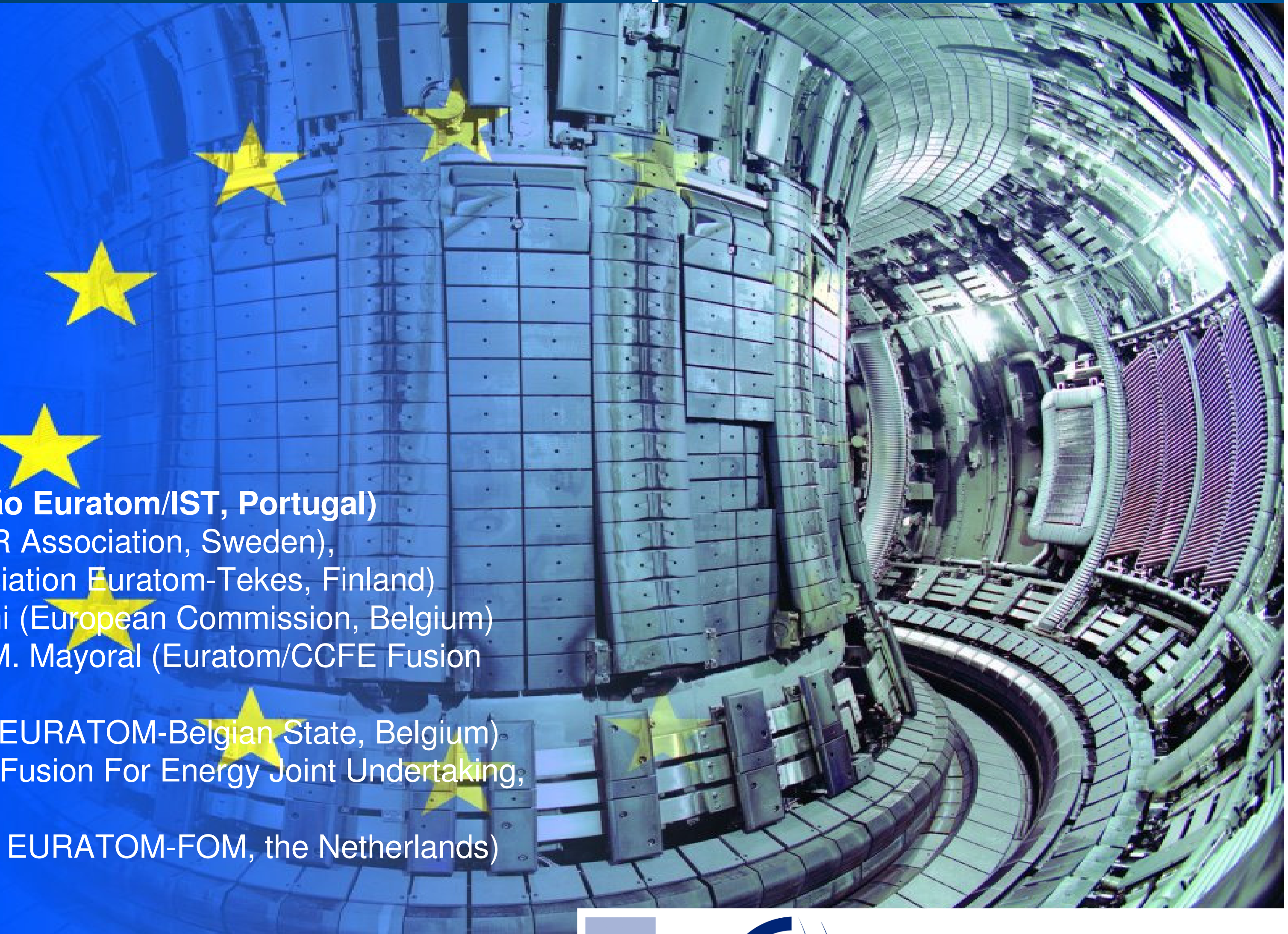
JET Intrinsic Rotation Studies and predictions for ITER



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- **Introduction**
- Intrinsic rotation with ICRF heating and usual low ripple
- Ripple effects on intrinsic rotation
- Extrapolation to ITER (comparison with Rice's scaling)
- Conclusions

What we mean by intrinsic rotation

Know sources of momentum input :

NBI: this is the largest source of momentum input in present tokamaks

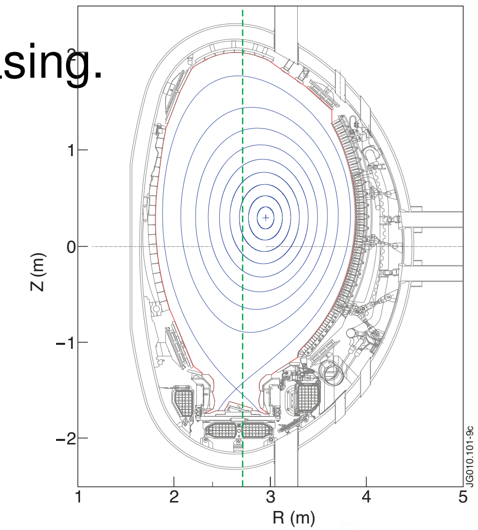
JET: NBI drives co-current rotation in the usual I_p and B_t configuration

ICRF: We can choose wave phasing to produce a small toroidal momentum in either co or counter-current direction. *These will not be discussed here* .

Flow drive from ICRF Mode conversion see Poster by Y. Lin, Friday Afternoon

Intrinsic rotation :

Rotation measured in plasmas with no momentum input:
such as Ohmic & ICRF heated plasmas with dipole antenna phasing.



This Poster: D plasmas, ICRF heating of H minority. dipole, resonance positions slightly off-axis on the high field side.

Motivation to study intrinsic rotation

In ITER and in fusion reactors: momentum input is expected to be small even with NBI
Other sources of rotation need to be found and understood.

Rice's scaling *(J. Rice NF 47, p.1618, 2007):* inter-machine intrinsic rotation scaling predicts a significant rotation for ITER (~300km/s).
WE NEED TO VERIFY IF JET ALSO FOLLOWS RICE' SCALING LAW

As an experimental tool: We need to understand how to control rotational shear and the direction of rotation

Rotation is a useful experimental tool as it plays many critical roles in plasma performance:

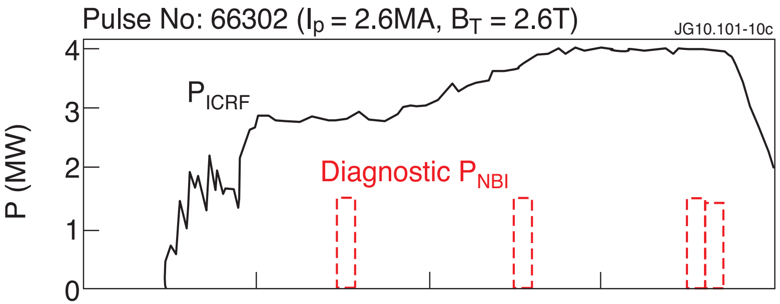
Turbulence suppression (ExB shear)
Mode stabilisation (RWM, NTM, sawteeth etc.)
Tolerance to magnetic field errors
Onset of H-mode and ITB

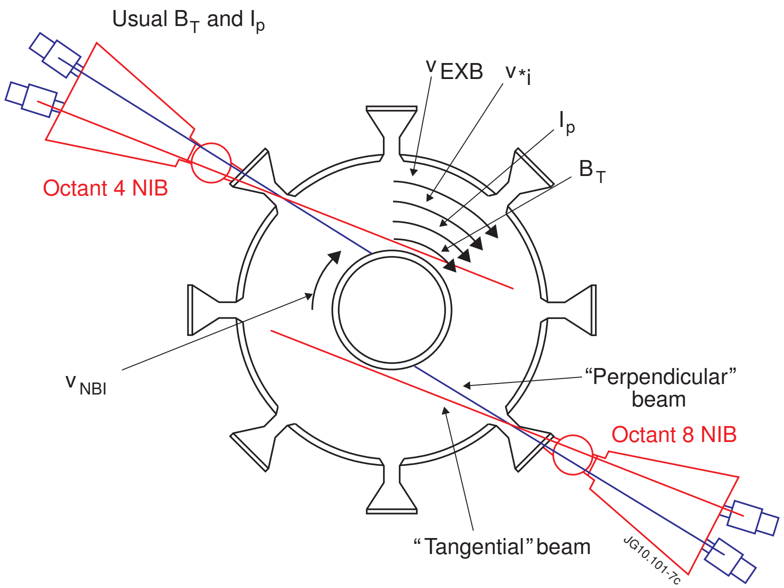
Co-rotation: (e.g. better ELMy H-modes)
Counter-rotation (QH Modes, small sawteeth regimes, etc)

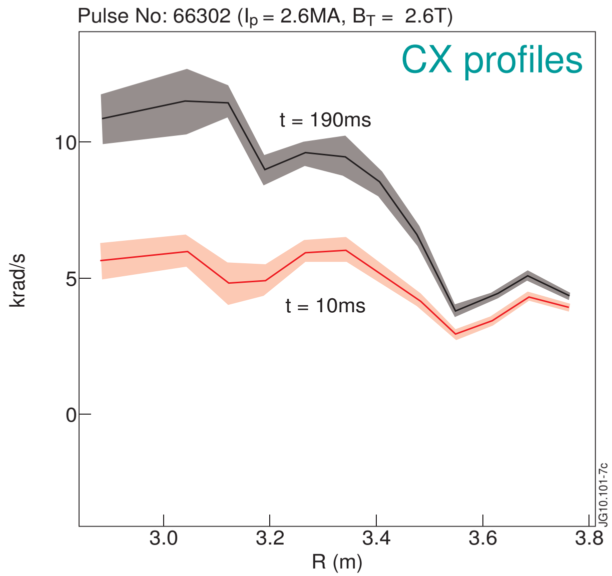
Rotation measurement tools

Charge exchange (CX) measurements:
Using NBI blips:

- Toroidal angular frequency profiles are obtained from charge exchange recombination spectroscopy of C+6 during NBI blips (PNBI~1.5 MW, up to 200 ms).
- JET has no dedicated diagnostic beam. To get CX data the heating NBI system has to be used. But this provides also rotation. In the usual JET configuration (BT//Ip) NBI plasmas are co-rotating.
- Only measurements taken within the first 30 ms are used.







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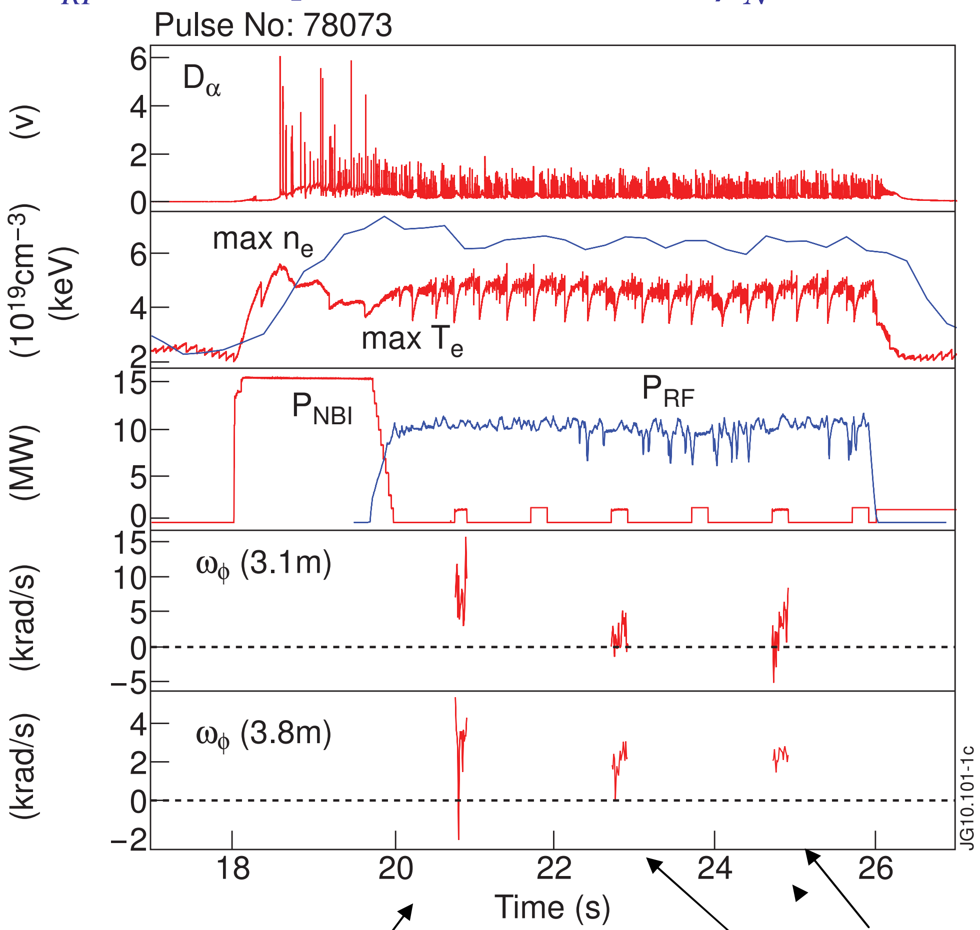
H-mode, low ripple δ=0.08%

(P_{RF}~10MW, Ip=2.5MA, BT=2.6T , β_N~1.3)



Ignore 1st blip
Too close to NBI pre-heating

Blips n. 2 and n. 3 show very small rotation <2krad/s at core and ~ 2krad/s at edge

For β_N up to 1.3%:
range of ω_ϕ values in H-mode is similar to observations in L-modes

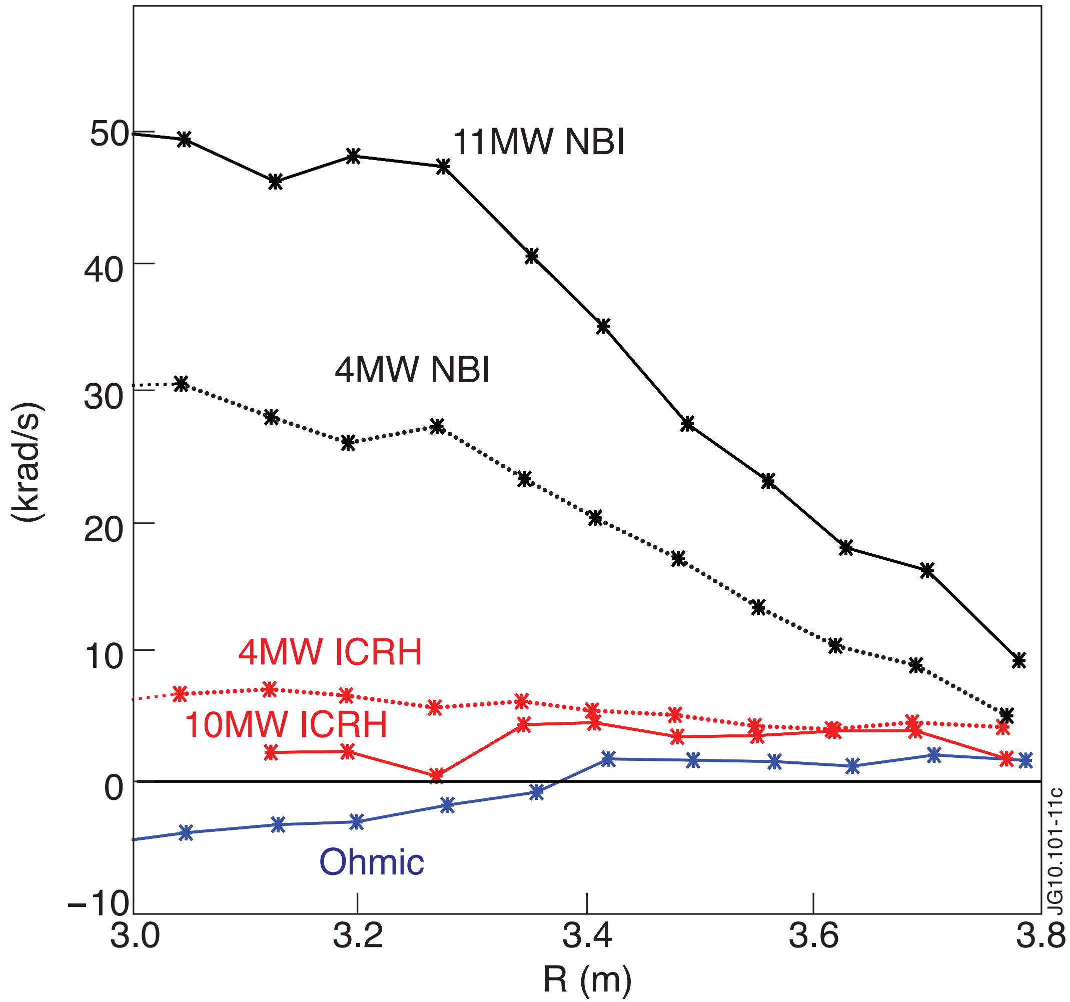
(L-modes:
Edge: co-rot. ωϕ = 2 – 7 krad/s
Core : either co- or counter-rot.
ωϕ = -10 – 10 krad/s
L-G Eriksson et al. in Plasma Phys. Control. Fusion 51 No 4 (April 2009) 044008.)

Low co-rotation observed in H-mode in part caused by MHD modes

As P_{ICRF} is increased, modes that displace fast-ions such as Fishbones and Core- TAEs are destabilised.

These are observed to increase counter-rotation by up to 10 krad/s

Summary: ICRF rotation, low ripple



For either L- mode or H-mode
Typical ω_ϕ <10 krad/s
$V\phi$ < 30 km/s

One order of magnitude smaller than in NBI plasmas that have a large momentum input

In L-mode:

ω_ϕ doesn't depend on P_{ICRF}
ω_ϕ doesn't depend on β_N
(L. Eriksson, PPCF 2009)

In H-mode (smaller database):

ω_ϕ doesn't appear to depend on either P_{ICRF} or β_N

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Effect of TF ripple on intrinsic rotation

- JET has 32 coils – very low levels of ripple (<0.08% at edge on low field side).

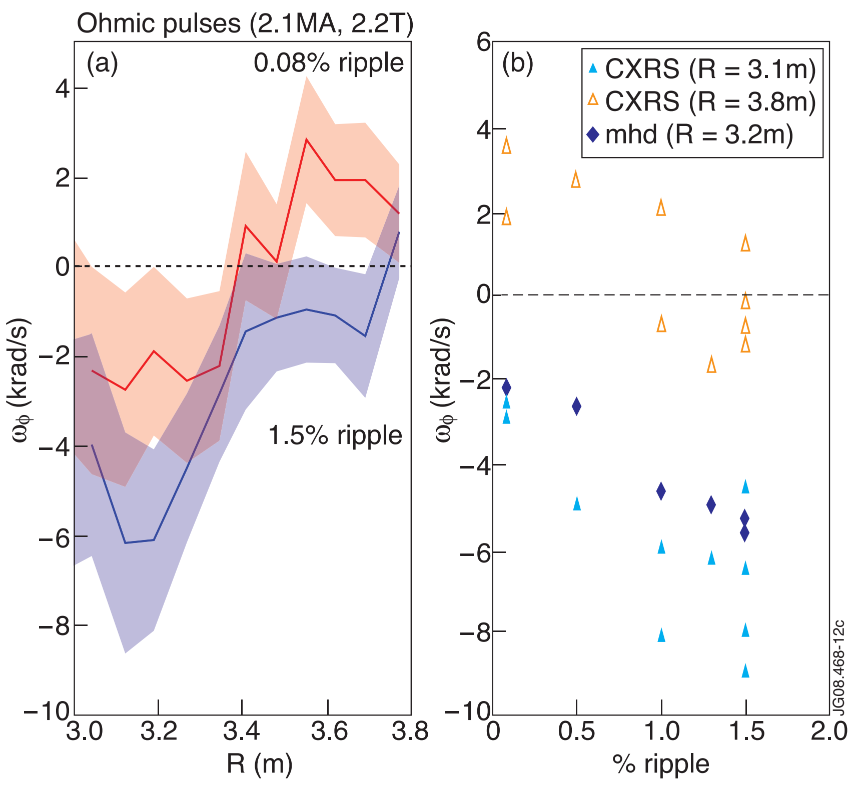
- JET can increase ripple by reducing current in every second TF coil
  ripple was increased from 0.08% to 1.5%
  ITER ripple values 0.5-1.2% (G. Saibene, EPS Conf. 2008)

NBI experiments
Ripple produced edge counter-rotation in JET plasmas with NBI co-injected momentum
(see Poster/Talk of P de Vries)

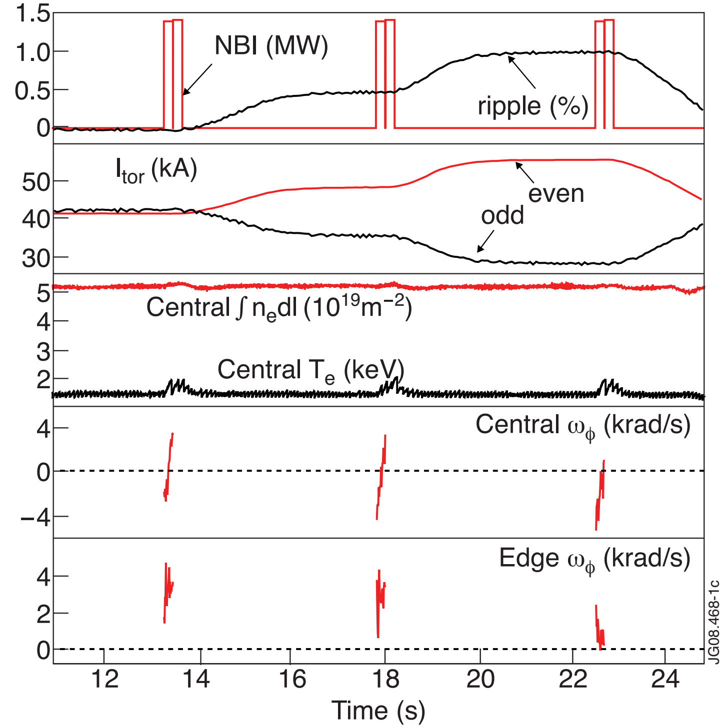
Intrinsic Rotation Experiments:
Ripple was found to have a significant effect on the rotation of both Ohmic and ICRF heated plasmas (M.FFNave et al, PRL 2010)

With ICRF heating and ripple ~1%, H-modes with edge and core counter-rotating were observed

Ohmic pulses with ripple

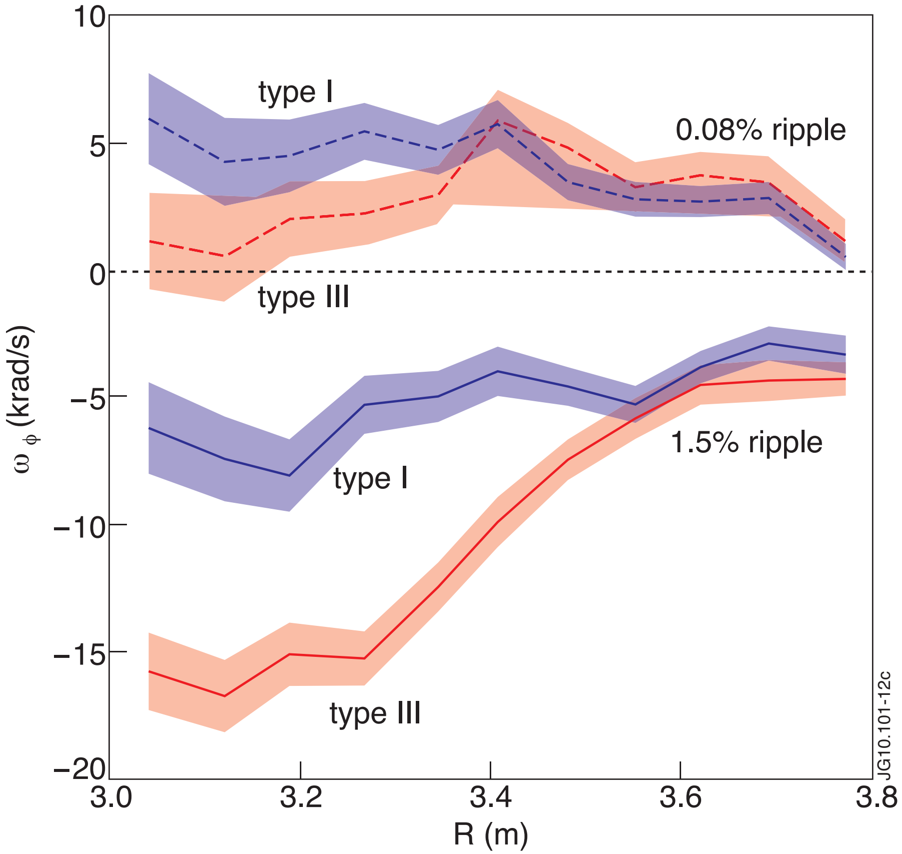


- *Counter-rotation increased with ripple.*
- *Edge and core effects are of the same order.*
- *The core effect is also seen in the frequency and direction of propagation of sawtooth pre- and post-cursor oscillations.*
- *Observed counter-rotation < than the predicted residual neoclassical C rotation [Shaing, PoP 2003], at ρ=0.9 (or R~3.8m): $\omega^{*NC}_{1/\nu} = 3.36/(B\ \theta)\partial_r Ti$ ~ -4.5±2.6 krad/s*



ICRF H-modes with ripple

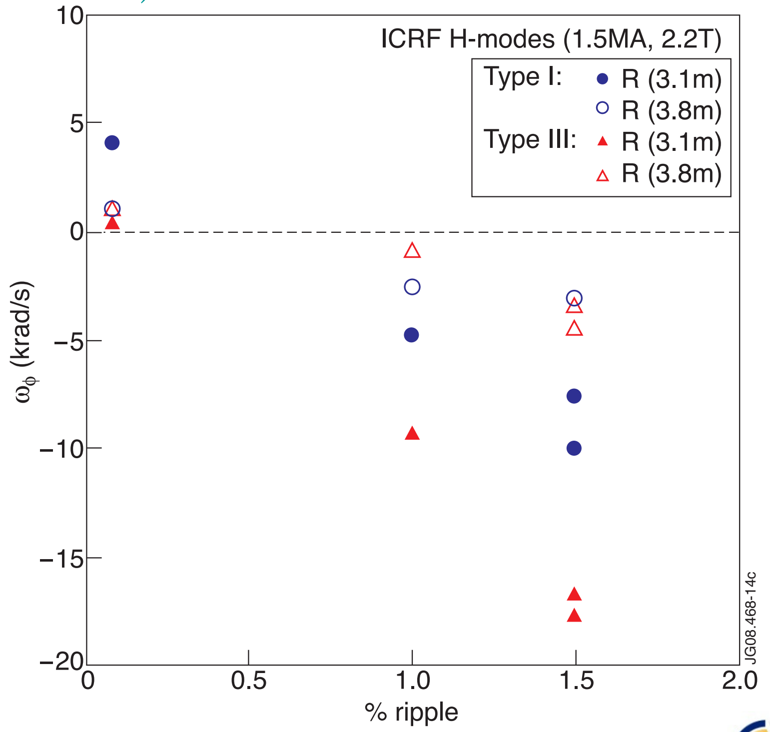
$\langle B_T \rangle = 2.1T$, $I_p = 1.5MA$, $P_{icrf} = 3MW$



1%-1.5% ripple: H-modes with the whole plasma column counter rotating

L-mode/type III ELM phases more counter rotating than in type I ELM phases.

(This is not associated with MHD modes)



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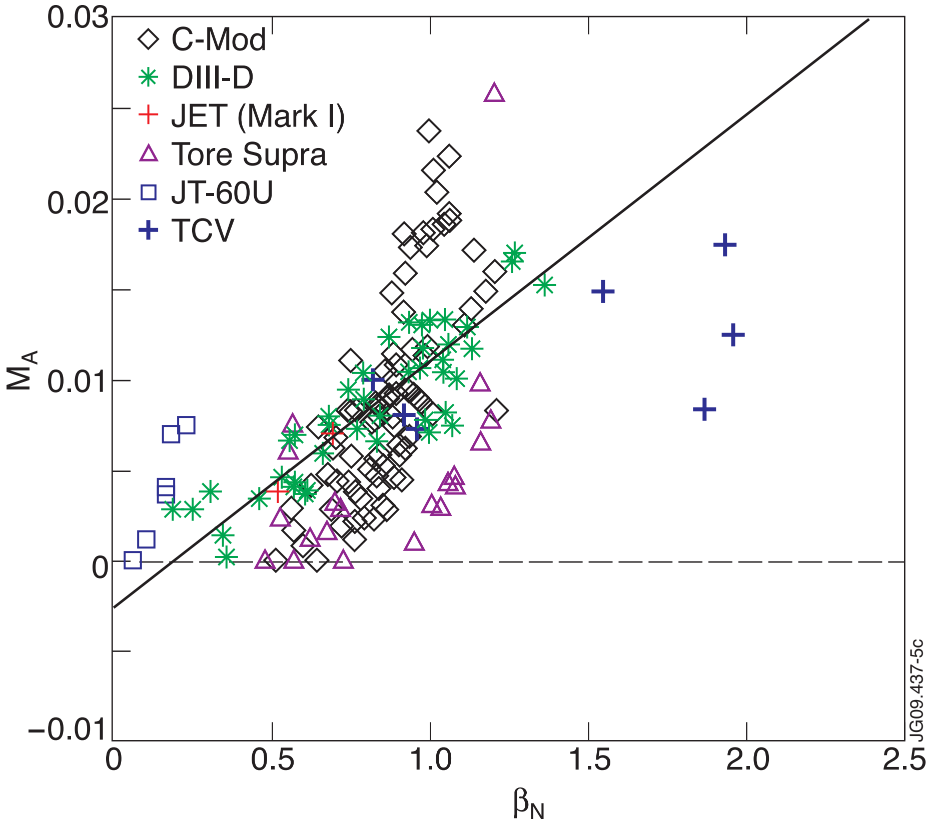
Inter-machine Scaling *(J.Rice et al, NF 2007)*



H-mode intrinsic rotation data from different devices compared using dimensionless parameters M_{th}, M_A.

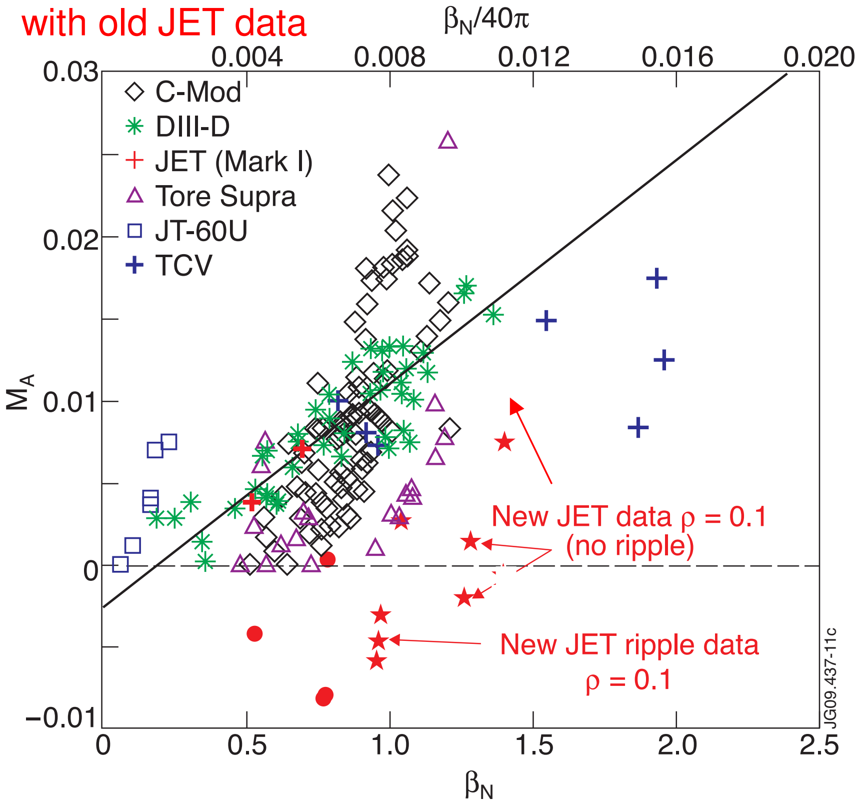
M proportional to β_N

Predicted toroidal rotation for ITER: $v_\phi \geq 300$ km/s

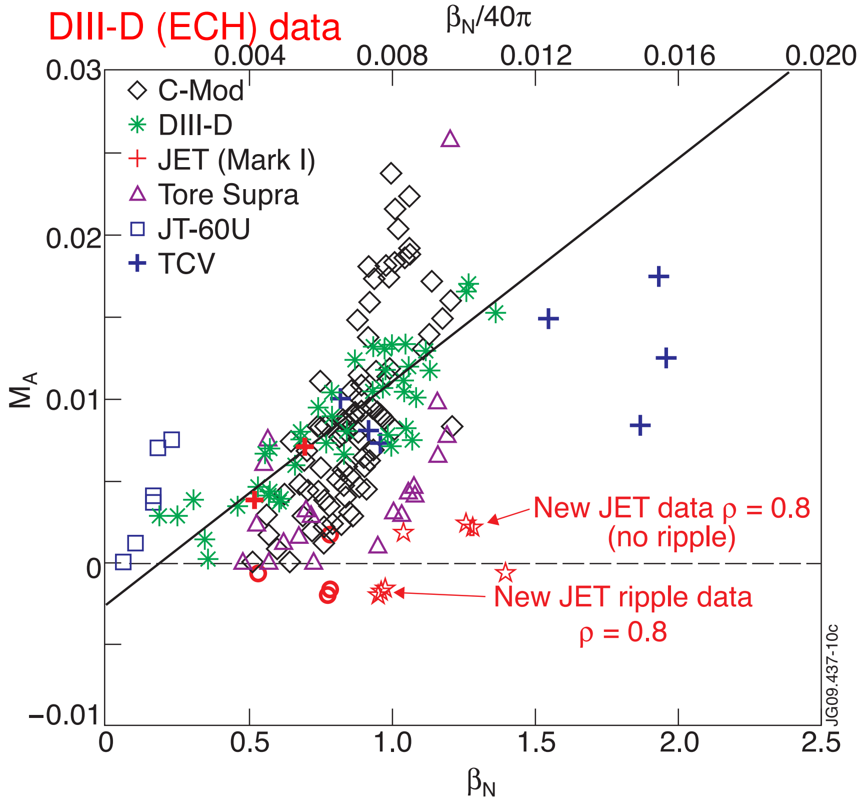
JET data (*Mark I divertor, 1994-95)* ICRF, (measured with X-ray crystal spectrometer of Ni+26)
The high values of co-rotation at the plasma centre ~20krads/s are no longer observed

Inter-machine Scaling (*J.Rice et al, NF 2007*) +new JET data

New JET Data at r=0.1 to be consistent with old JET data



New JET Data at r=0.8 to be consistent with DIII-D (ECH) data



- JET ICRF H-mode data doesn't follow Rice's scaling law.
- For 0.08% ripple: Mach-Alfven ~ 10 times smaller for same β_N
- For 0.5% ripple JET rotation ~ zero.
- For 1-1.5% ripple JET plasmas are counter rotating

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Conclusions

➢ **JET Low Ripple: ELMy H-modes ω_ϕ values similar to those observed in L-modes**

➢ **With Ripple**

- **Ripple has a significant effect on the rotation of Ohmic and of ICRH plasmas**
- Ripple drives counter rotation
- Ripple effect seen both in the edge and core
- Indicates a strong torque due to non-ambipolar transport of thermal ions and with ICRF a fast ions.

➢ **Rice's Scaling and JET data**

- Intrinsic Rotation in JET has no clear dependency on β_N
- JET ICRH rotation is very low, below Rice' scaling law.
- For relevant ITER ripple values: 0.5% ripple, JET ICRF plasmas are hardly rotating.
  1% ripple, JET ICRF plasmas are counter rotating
- **JET data indicates that ITER intrinsic rotation may be smaller than predicted by the Rice's scaling**
- Several factors play a role in determining JET intrinsic rotation:
  ripple, MHD modes, location of ICRH resonance, H-mode scenario
- Further experiments are needed to clarify the roles of:
  plasma volume, SOL conditions, possibly other effects