A TRANSPORT PERSPECTIVE ON BURNING PLASMA MEASUREMENT NEEDS

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OVERVIEW

- New transport science to be confronted in a BPX
- Comments on profile spatial resolution requirements
- Comments on measurement needs for detailed transport physics understanding

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"MEASUREMENTS ARE THE WINDOW TO THE SCIENCE"

- Is science important in a BPX whose primary goal is to produce plasmas with Q~10?
  - YES!
    - ★ It is essential that we comprehensively characterize the physics of burning plasmas in the next step device, so as to justify and enable construction of a succeeding device, such as a DEMO or ETR and in order contribute to ICCs
    - ★ A BPX is an experiment - we are not certain what will happen
  - Diagnostic set is key enabler in extent of transport physics to be extracted from BPX (flexibility)
- Investigation of burning plasma physics is a major goal of ITER and FIRE

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WHAT SCIENCE ISSUES WILL WE CONFRONT IN A BPX?

- New elements in a burning plasma:
  - Self-heated by fusion alphas
  - Significant isotropic energetic population of 3.5 MeV alphas
  - Larger (nondimensional) device scale size

- Plasma is now an exothermic medium and highly non-linear

- New science phenomena to be explored:
  - Q~5
    - ★ Alpha effects on stability and turbulence
  - Q~10
    - ★ Strong nonlinear coupling between alphas, pressure driven current, turbulent transport, MHD stability and boundary plasma

- Conclusion: much of the new science is transport/turbulent related

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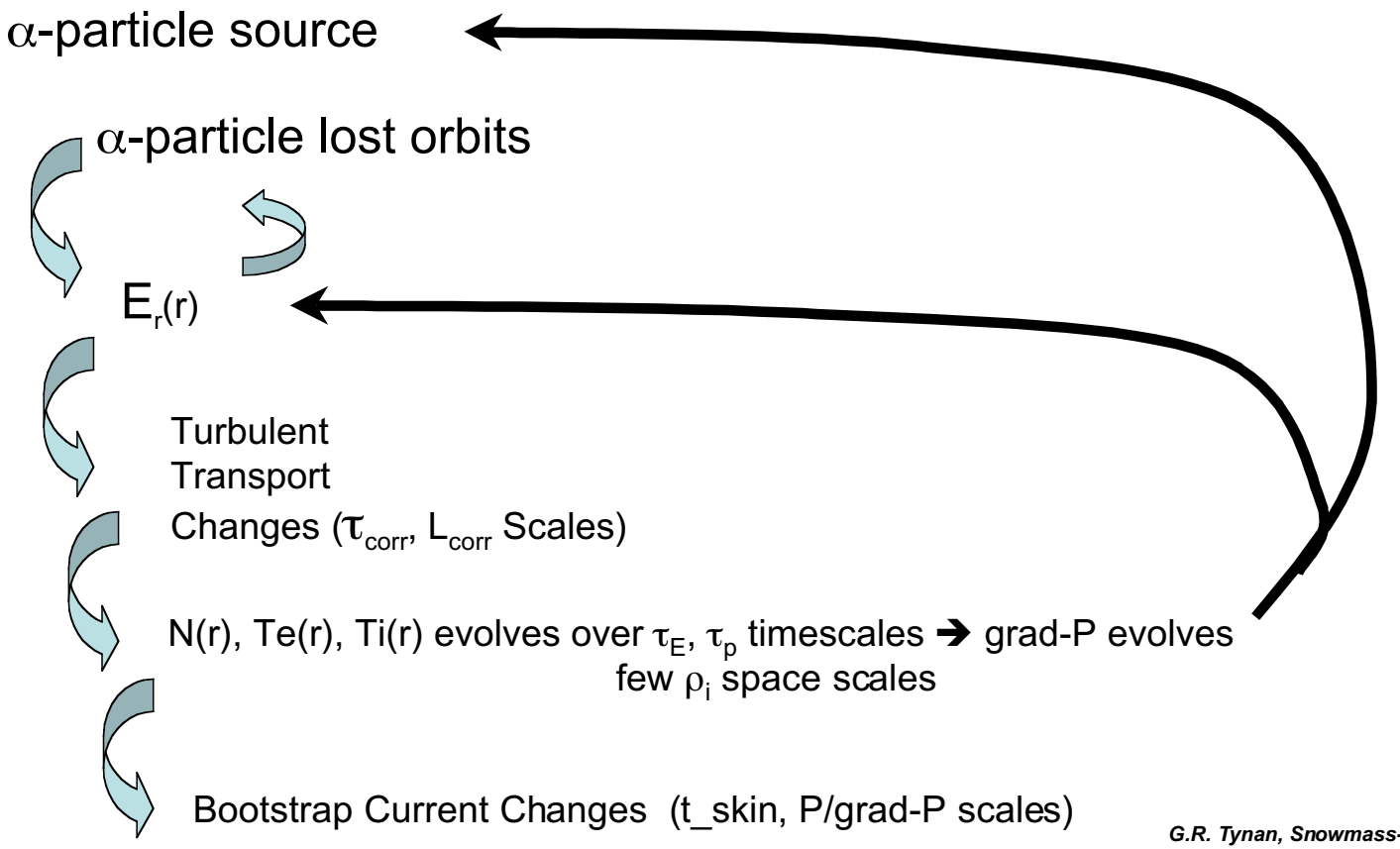
EXAMPLE OF POSSIBLE NON-LINEAR COUPLING BETWEEN E_r, TURBULENCE, CONFINEMENT AND CURRENT PROFILE



G.R. Tynan, Snowmass-2002
Community Issues Forum

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- **Courtesy of G. Tynan, UCSD**

PRIMARY TRANSPORT RELATED MEASUREMENT NEEDS

- Measurements for:
  - Calculation of transport coefficients
    - ★ Ion and electron thermal, particle and momentum diffusivities, helium ash and impurity transport
  - α-particle distribution
  - Detailed physics understanding
    - ★ q-profile, plasma flows, E_r, turbulence

- For discussion will use ITER diagnostic set as a strawman
  - Most developed set of BPX diagnostics

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MEASUREMENT NEEDS ARE STRONGLY IMPACTED BY ADVANCED MODES OF OPERATION

- AT operation is envisaged on all three BPX, and is essential for long pulse, steady-state operation on ITER

- Improved transport regimes, and ITB-based regimes in particular, can have substantial gradients at variable radii
  - Requires much improved measurement spatial resolution
    - ★ Need to resolve width of steep gradient zone - no predictive capability on width at present
  - Accurate high resolution q profile measurements are now critical

- Profile measurements needed for transport analysis
  - T_e, T_i, n_e
  - q
  - Heating deposition profile, α-particle distribution
  - Z_{eff}, He ash and impurity profiles
  - Plasma rotation, E_r

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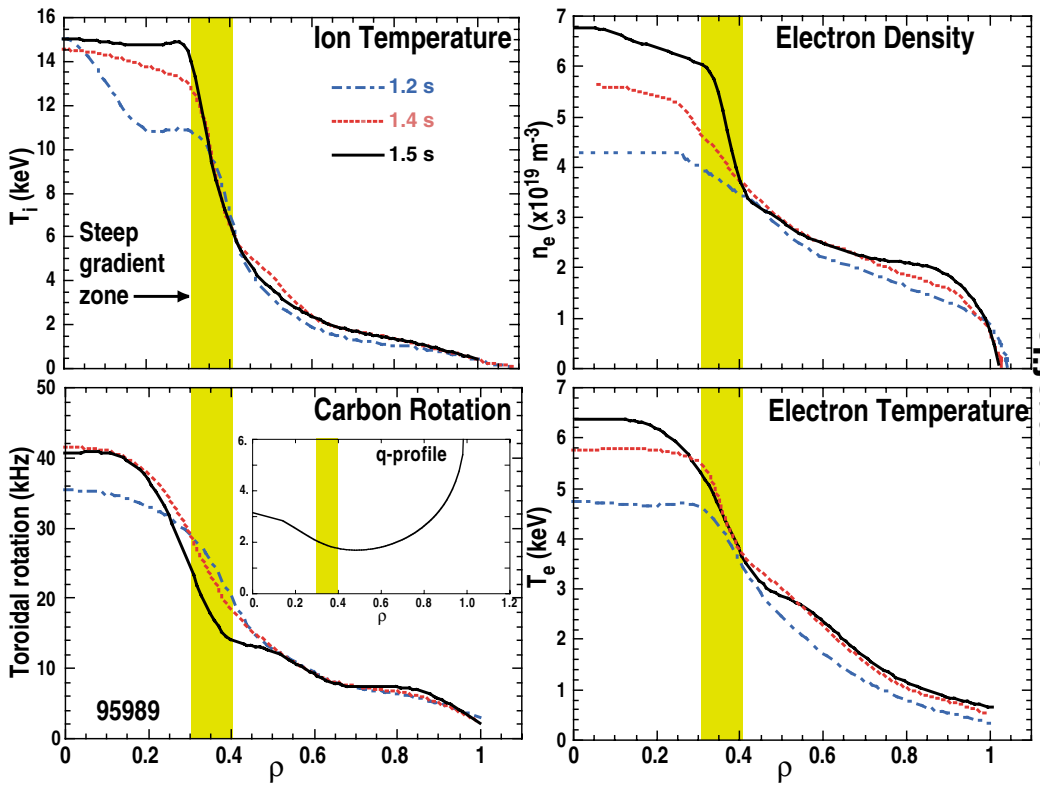
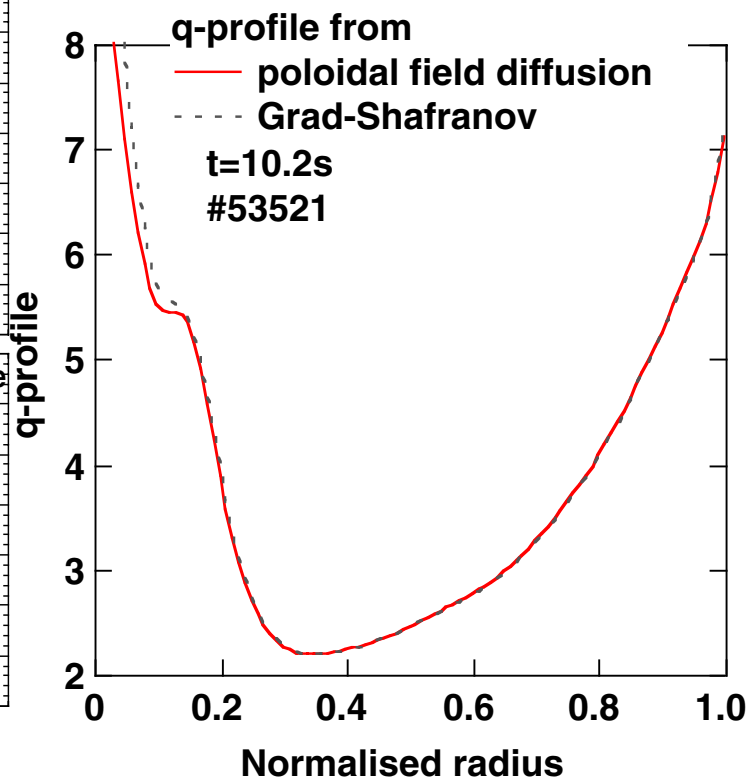
EXAMPLES OF STRONG GRADIENTS WITH ITBs

- DIII-D ITB profiles with strong NCS (Doyle, PPCF 2000)



- JET q profile with strong NCS
  - Litaudon, ITPA 2002



- JT-60U profiles provide even more dramatic examples
- Do not know how ITB width will scale to BPX

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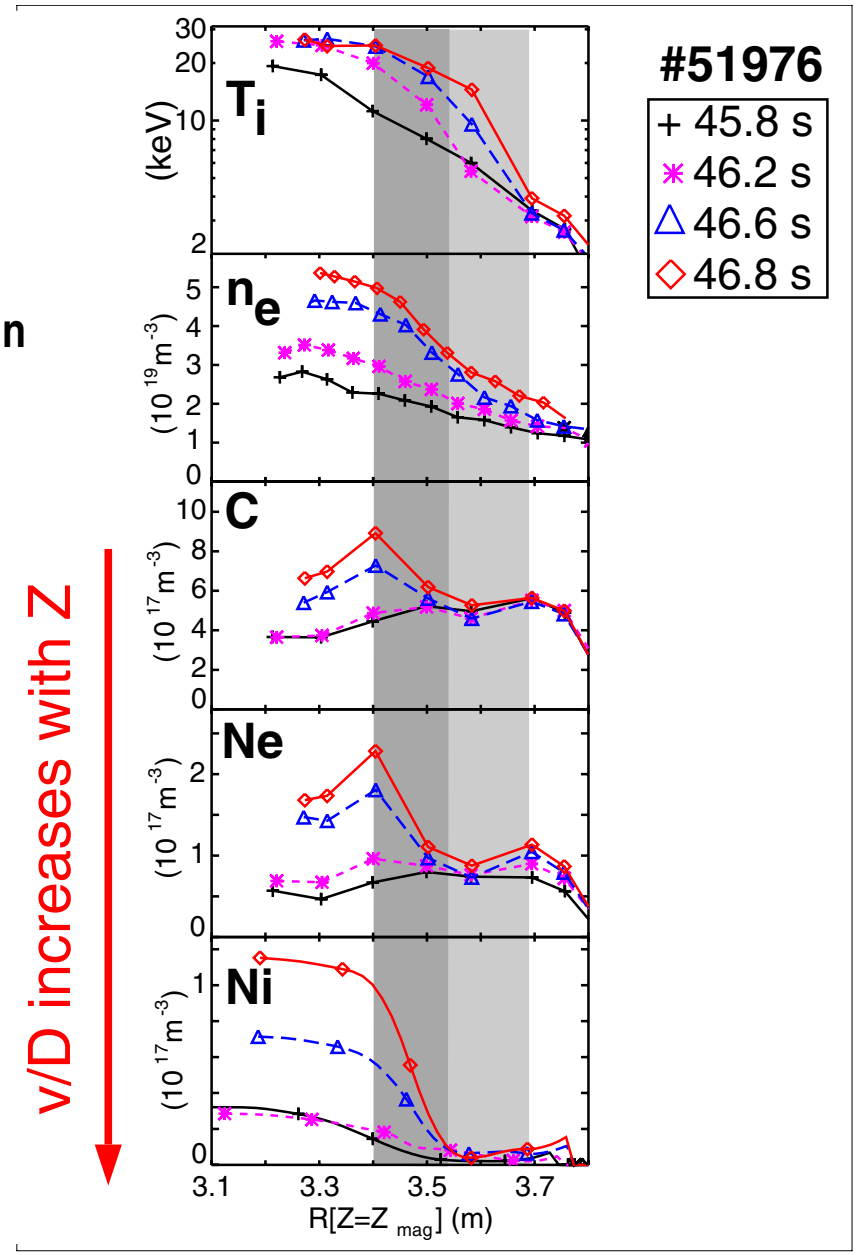
IMPURITY PROFILES CAN ALSO HAVE LARGE GRADIENTS WITH ITBs

- JET impurity transport is neoclassical, leading to high-Z impurity accumulation (Dux EPS 2001, Litaudon, ITPA 2002)
  - Note largest profile gradient is in Ni



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IMPROVED SPATIAL RESOLUTION NEEDED FOR ITER PROFILE MEASUREMENTS

- Target ITER profile spatial resolution varies by parameter:
  - a/30 T_e, n_e, V_{TOR}
  - a/20 q (not currently being met, no core coverage)
  - a/10 T_i, alphas, Z_{eff}, He and impurity profiles
- a/10 spatial resolution is insufficient!
- Uniform spatial resolution desirable for transport analysis
- Time resolution also varies by parameter, from 10-100 ms
  - Is 100 ms sufficient for perturbative impurity transport studies?

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ADVANCED TRANSPORT MEASUREMENT NEEDS

- q-profile, turbulence (low- and high-k density, magnetic and temperature fluctuations), E_r/flows
  - Essential for physics understanding of AT operation in BPX
    - ★ Non-linear couplings, improved confinement/ITB access, electron thermal transport, etc.
  - Essential for quantitative evaluation of simulations and models
  - May be necessary for control
    - ★ Changes in turbulence and flows may be first indicator of gain/loss of improved transport modes

- Detailed turbulence measurements are viewed as an essential component of transport studies in the US. Currently we are seeing transition from predominantly qualitative to increasingly quantitative comparisons to theory and simulations
  - Can anticipate that quantitative comparisons will be routine within a decade

- α-particle measurements are essential because of new physics effects

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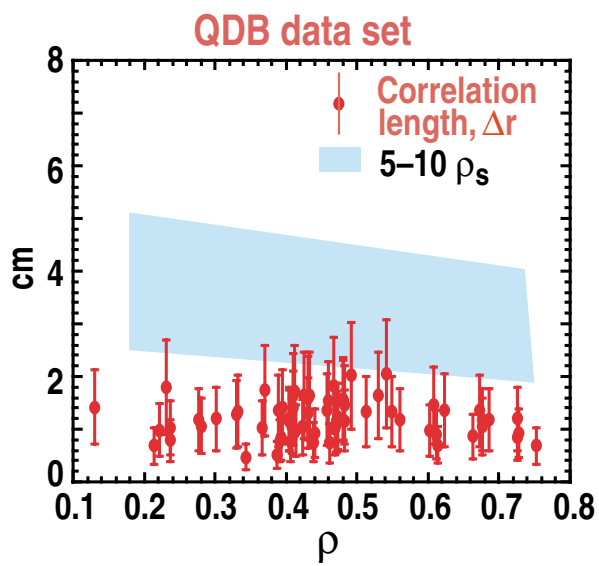
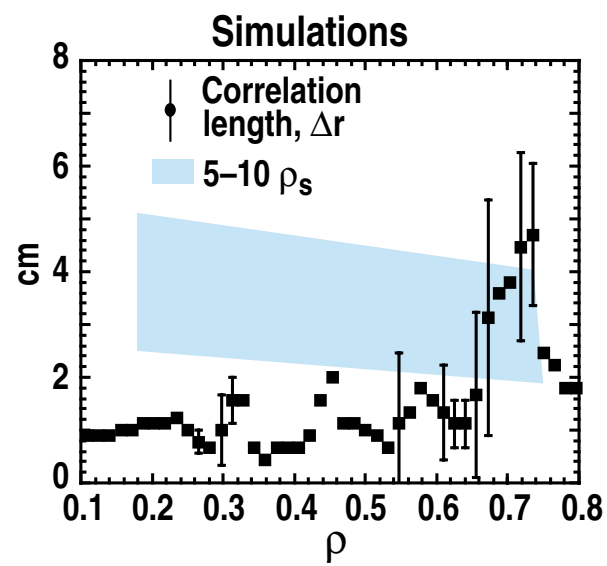
QUANTITATIVE COMPARISONS OF TURBULENCE MEASUREMENTS TO GYROKINETIC CODES INITIATED

- Example from Rhodes et al, APS 2001,
  - Other examples also exist, e.g. Ross et al, POP 2002, etc.

- In QDB plasmas, core correlation lengths are significantly lower than observed in L–mode



- Initial modeling using the UCAN global gyrokinetic code tracks core experimental trends and magnitude
  - ITG turbulence in circular geometry



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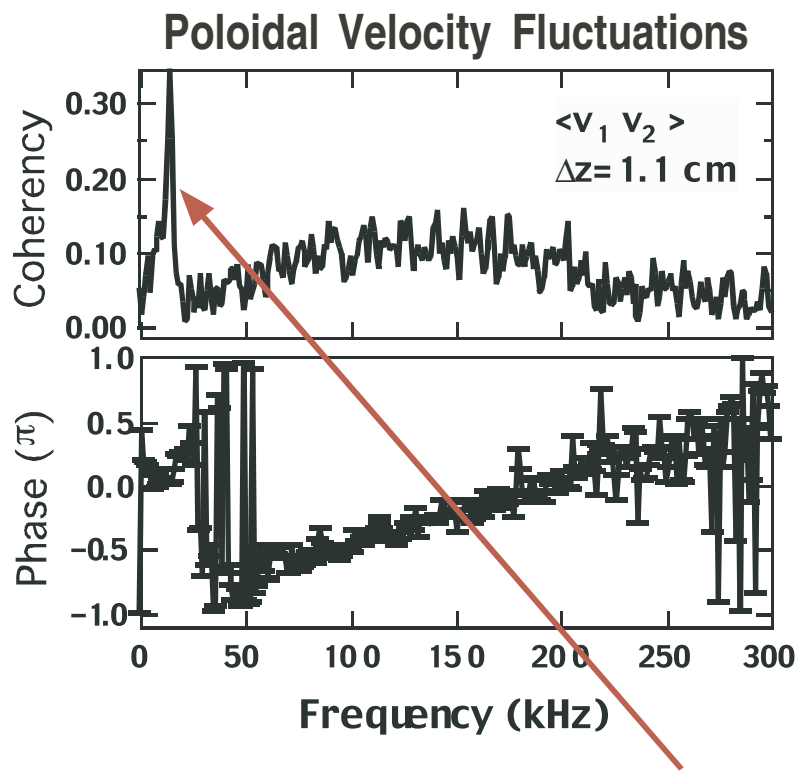
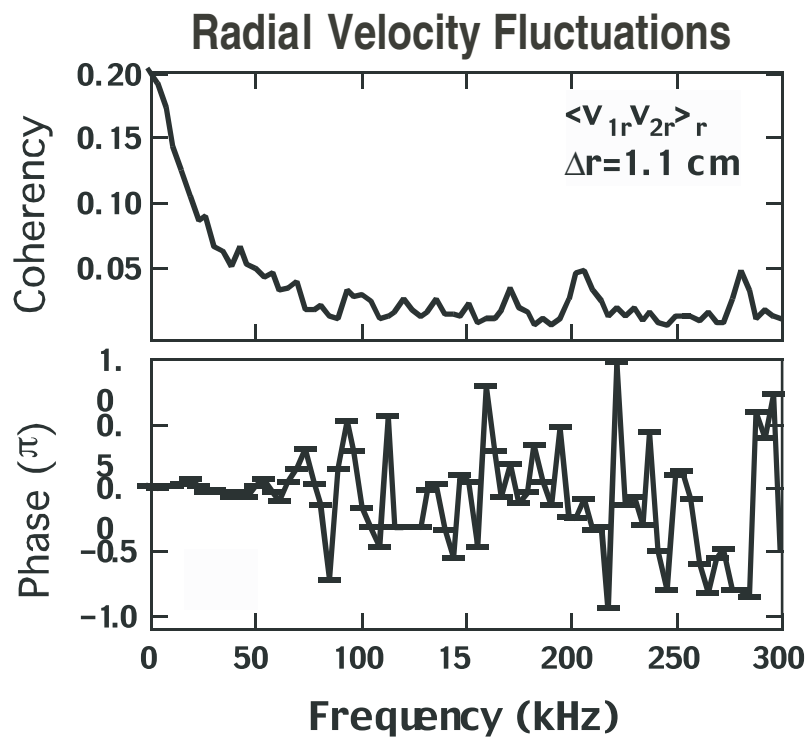
TURBULENCE MEASAUREMENTS PROVIDE CRITICAL TESTS OF THEORY PREDICTIONS, SUCH AS ZONAL FLOWS

- Potential zonal flow features have been observed in in DIII-D using 2-D Beam Emission Spectroscopy (BES) turbulence measurements
  - G. McKee, Varenna Diagnostic Workshop, 2001





Long-wavelength coherent feature: Zonal Flow?

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LEAST DEVELOPED DIAGNOSTIC SET ON ITER IS THAT FOR ADVANCED TRANSPORT ANALYSIS

Assessment of Measurement Capability (November 2001)

GROUP 1a Measurements For Machine Protection and Basic Control	GROUP 1b Measurements for Advanced Control	GROUP 2 Additional Measurements for Performance Eval. and Physics
Plasma shape and position, separatrix- wall gaps, gap between separatrixes	Neutron and α-source profile	Confined α-particles
Plasma current, q(a), q(95%)	Helium density profile (core)	TAE Modes, fishbones
Loop voltage	Plasma rot. (tor and pol)	T_e profile (edge)
Fusion power	Current density profile (q-profile)	n_e, T_e profiles (X-point)
$\beta_N = \beta_{tor}(aB/I)$	Electron temperature profile (core)	T_i in divertor
Line-averaged electron density	Electron den profile (core and edge)	Plasma flow (divertor)
Impurity and D,T influx (divertor, & main plasma)	Ion temperature profile (core)	$n_T/n_D/n_H$ (edge)
Surface temp. (div. & upper plates)	Radiation power profile (core, X-point & divertor)	$n_T/n_D/n_H$ (divertor)
Surface temperature (first wall)	Z_{eff} profile	T_e fluctuations
Runaway electrons	Helium density (divertor)	n_e fluctuations
'Halo' currents	Heat deposition profile (divertor)	Radial electric field and field fluctuations
Radiated power (main pla, X-pt & div).	Ionization front position in divertor	Edge turbulence
Divertor detachment indicator (J_{sat}, n_e, T_e at divertor plate)	Impurity density profiles	MHD activity in plasma core
Disruption precursors (locked modes,m=2)	Neutral density between plasma and first wall	
H/L mode indicator	n_e of divertor plasma	
Z_{eff} (line-averaged)	T_e of divertor plasma	
n_T/n_D in plasma core	Alpha-particle loss	
ELMs	Low m/n MHD activity	
Gas pressure (divertor & duct)	Sawteeth	
Gas composition (divertor & duct)	Net erosion (divertor plate)	
	Neutron fluence	

Expect to meet meas. reqs; maybe/mabe not; expect not to meet meas reqs.

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COMMENTS ON PLANNED ITER DIAGNOSTICS

- Measurement set needed for advanced transport analysis is in red coloring (not meeting requirements); q profile, α-particle measurements, turbulence diagnostics and E_r
- Reason for red coloring differs for different diagnostics:
  - Some, such as q-profile measurements, have been looked at in detail, and are not meeting requirements because of technical challenges in implementing the measurements
  - Others, such as turbulence measurements, have simply not been looked at in detail due to low priority
- Some of the measurements currently in black (meeting requirements) may not in fact be adequate for advanced operating modes due to insufficient target spatial resolution
- Available ITER midplane ports are already full and diagnostics cannot readily be added later
  - Already too late to add turbulence and E_r measurements to ITER?

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POINTS FOR DISCUSSION

- Provide an EXCELLENT diagnostic suite on a BPX, not just adequate

- From a transport perspective, anticipated ITER measurements need further enhancement:
  - Increased spatial resolution, with better uniformity
  - Accurate, high spatial resolution q profile measurement
  - E_r/flows and low and high-k turbulence measurement set
  - Confined alpha measurements

- Is it already too late to add turbulence measurements to ITER?
  - Available midplane ports are already completely full!

- FIRE and IGNITOR would be worse than ITER due to more limited access?

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