Tokamak Plasma Control

Can we sustain fusion reactor condition stably?

- **Tokamak plasma control categories**
  - **Discharge control: Start-up and shape (equilibrium with magnetics)**
  - **Discharge kinetic control**
    (transport and confinement, particle and power handling)
  - **Advanced discharge control (stability, ELM and disruption)**

Tokamak Plasma Control

Selected ITER control functions

Physics of Plasmas 22, 021806 (2015)

TABLE I. Summary of selected control functions in ITER, along with principal control goals and actuators. (PF = poloidal field, CS = central solenoid, VS3 = vertical stability coil circuit #3, NBI = neutral beam injection, ICRH = ion cyclotron resonant heating, RMP = resonant magnetic perturbation, ECH/ECCD = electron cyclotron heating/current drive, EFC = error field correction).

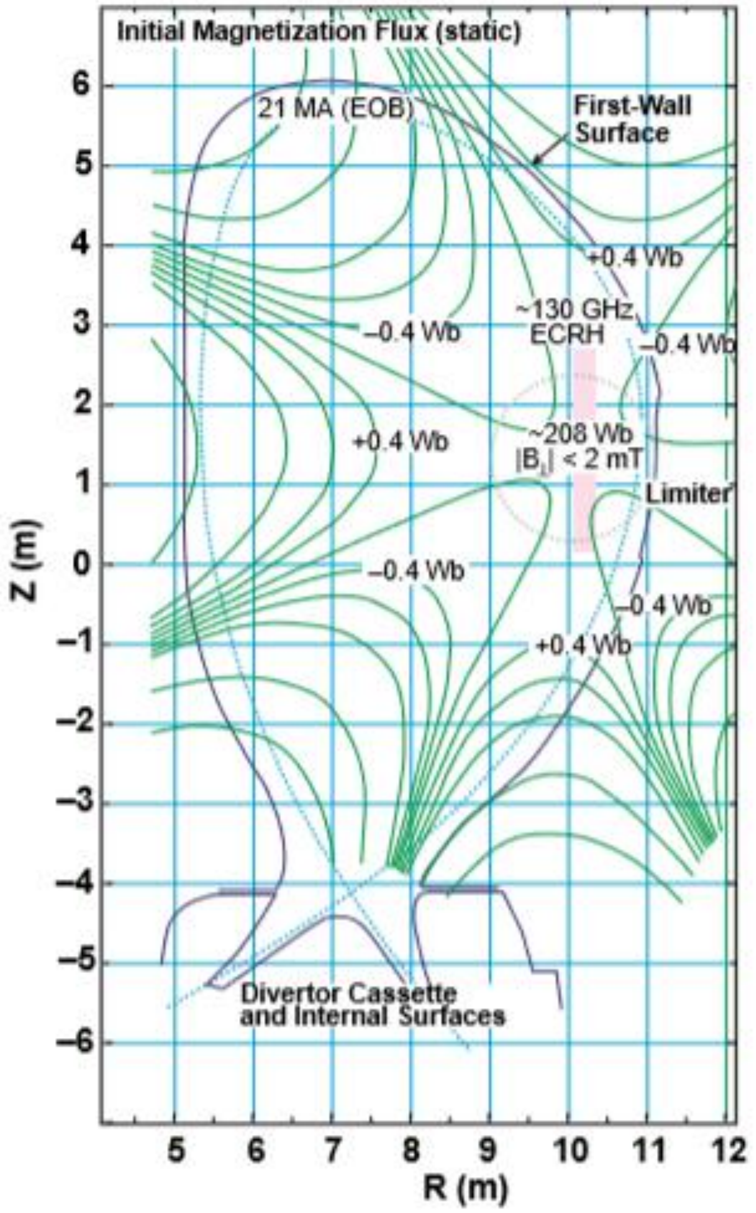
Control Category	Principal Control Goals/Control Quantities	Actuators
Plasma equilibrium	Boundary, position Divertor magnetic configuration	PF coils
Plasma current	Magnitude of plasma current Internal inductance	CS coils
Vertical stability	Vertical stabilization Vertical position (partial)	PF coils, in-vessel VS3 coils
Kinetics	Core electron density Stored energy/beta	Fueling pellets, gas, NBI, ICRH
Burn state	Fusion gain Fusion alpha power Confinement	Fueling pellets, gas, NBI, ICRH, in-vessel RMP coils
Divertor	Target heat flux Divertor radiation Degree of detachment, electron temp.	Impurity gas injection, fueling
Current profile	Internal inductance Q profile Proximity to MHD control boundaries	CS coils, ECH/ECCD
ELM control	ELM frequency, amplitude ELM stability	RMP coils, pacing pellets
Sawtooth control	Sawtooth stability Sawtooth frequency	ECH, ICRH
TM control	TM stability TM island size Mode rotation	ECH/ECCD, in-vessel RMP coils, NBI, ICRH, EFC coils
Fast particles	Stabilize Alfven Eigenmodes Regulate fast particle confinement	ECH/ECCD, ICRH, NBI, in-vessel RMP coils
Error field	Error field correction Rotation	Error field correction coils, in-vessel RMP coils
Disruption mitigation	Rapid uncontrolled shutdown Mitigate disruption effects	CS/PF coils, VS3 coils, Disruption Mitigation System (impurity gas, shattered pellet injection)

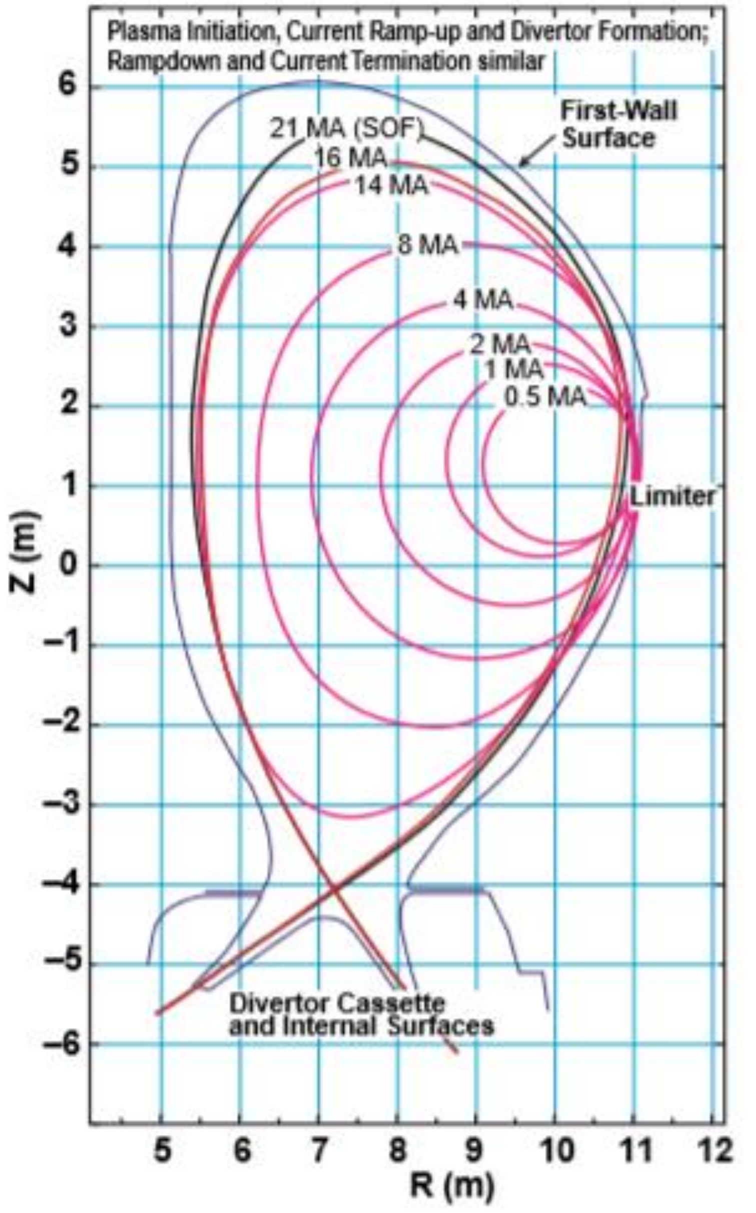
A significant amount of control physics understanding remains in order to complete such a robust ITER solution. Examples include:

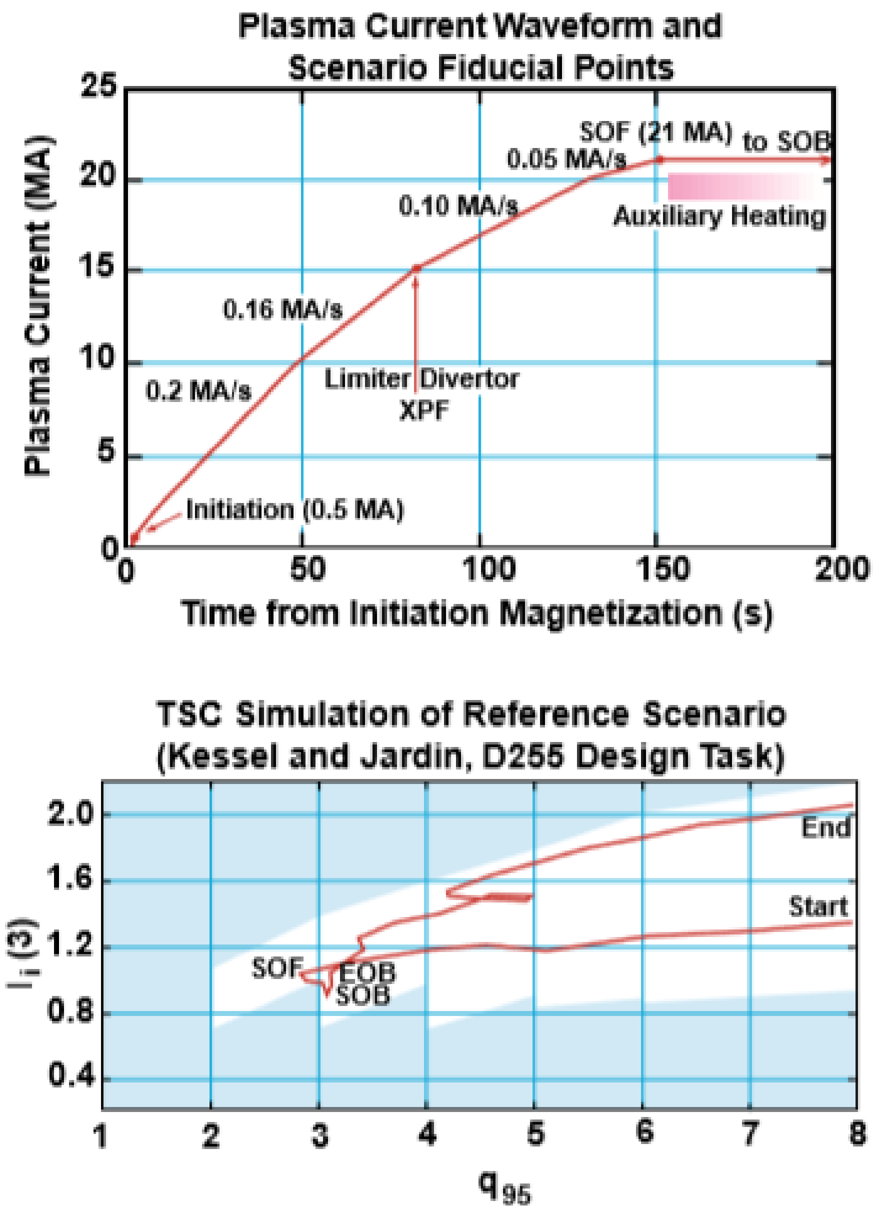
– Identification of key profile characteristics determining TM stability
– Size of effective TM seeds produced by disturbances such as sawteeth and ELMs
– Quantification of controllability/robustness metrics corresponding to seedless TM triggering
– Effective control methods for burn control
– Sufficient look-ahead predictive capability for profile evolution using real-time data
– Reliable real-time calculation of proximity to stability and controllability boundaries
– Physics-based models for many relevant control functions, including noise, disturbance, and robustness specifications
– Scenarios for exception handling response to minimize or prevent disruptions

Discharge Start-up Control

Nucl. Fusion 39, 2577 (1999)

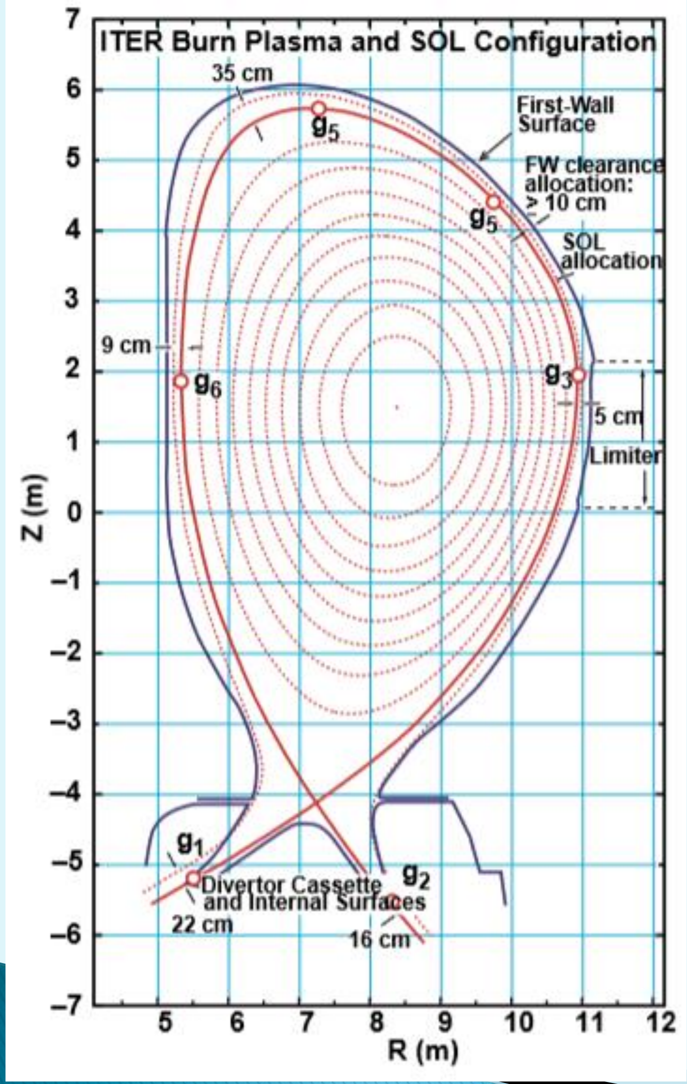


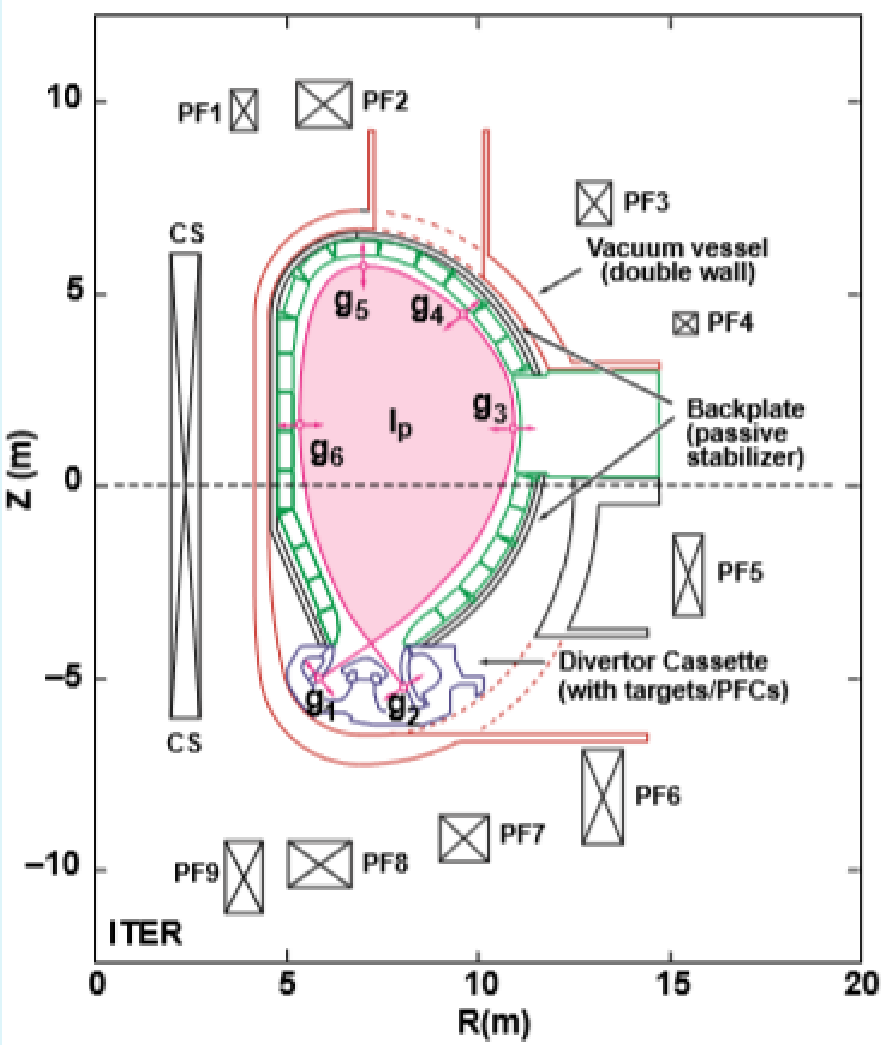


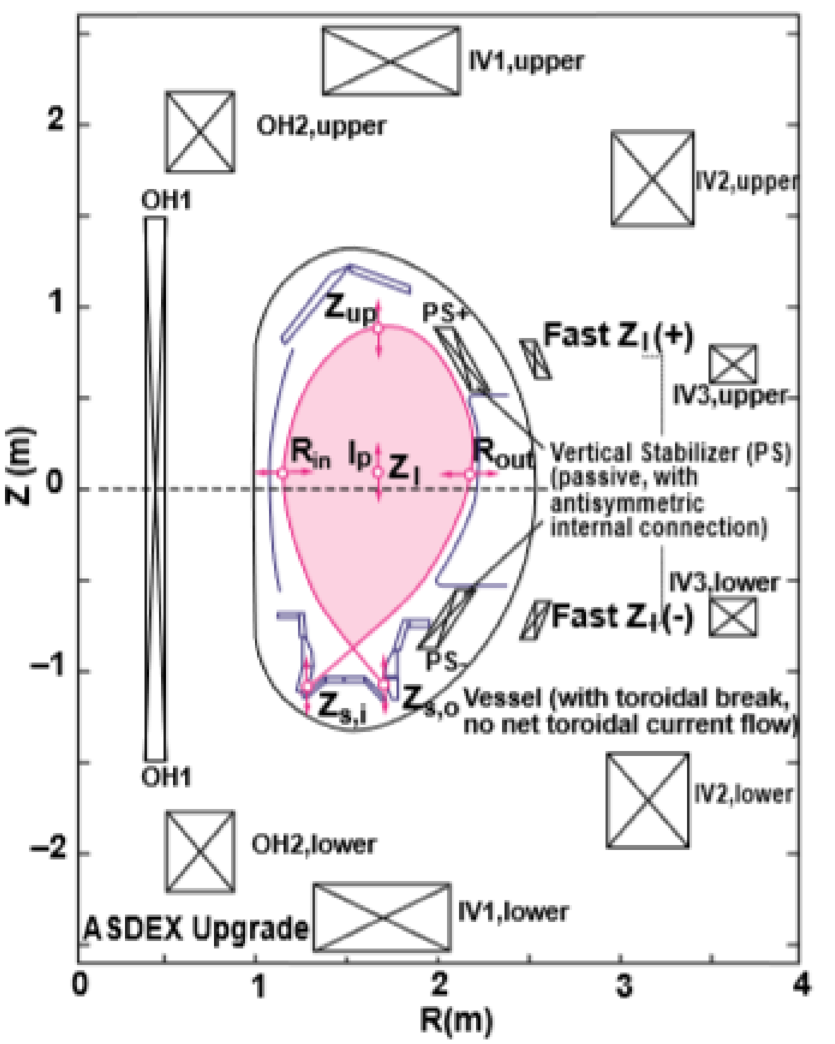


Discharge Shape Control

Nucl. Fusion 39, 2577 (1999)







Discharge Kinetic Control

Nucl. Fusion 39, 2577 (1999)

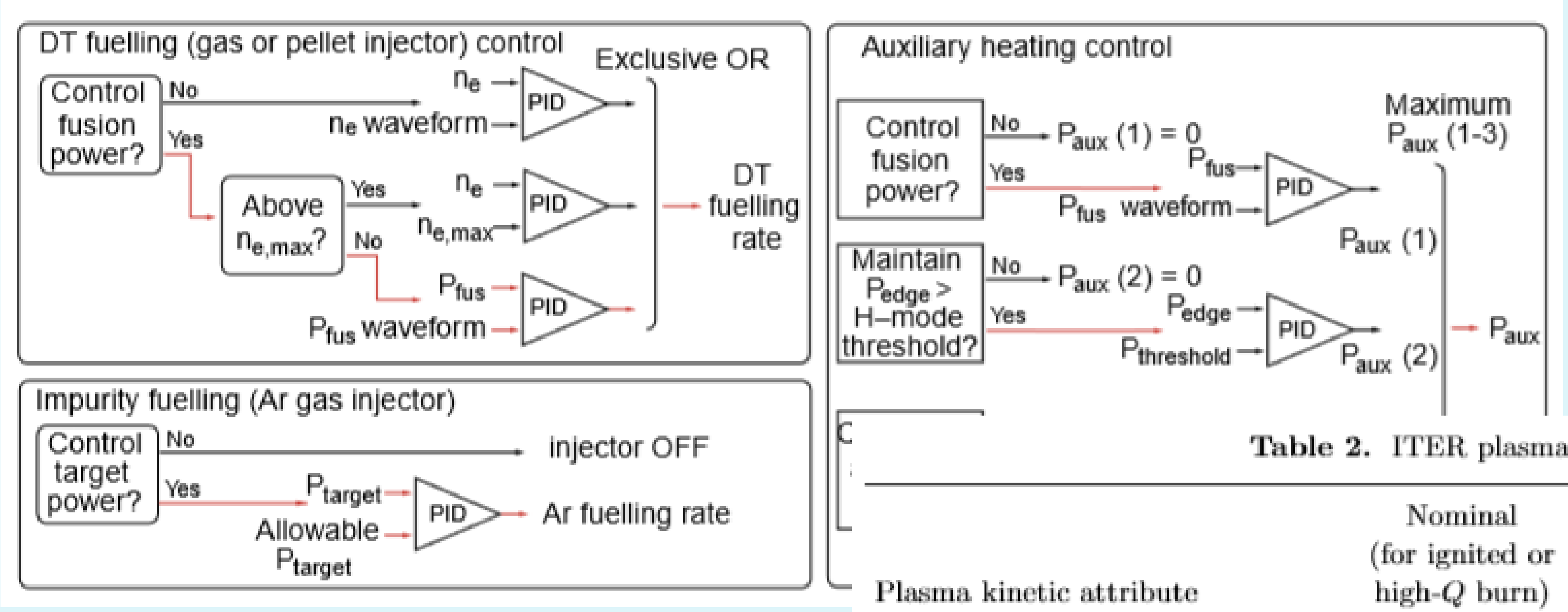


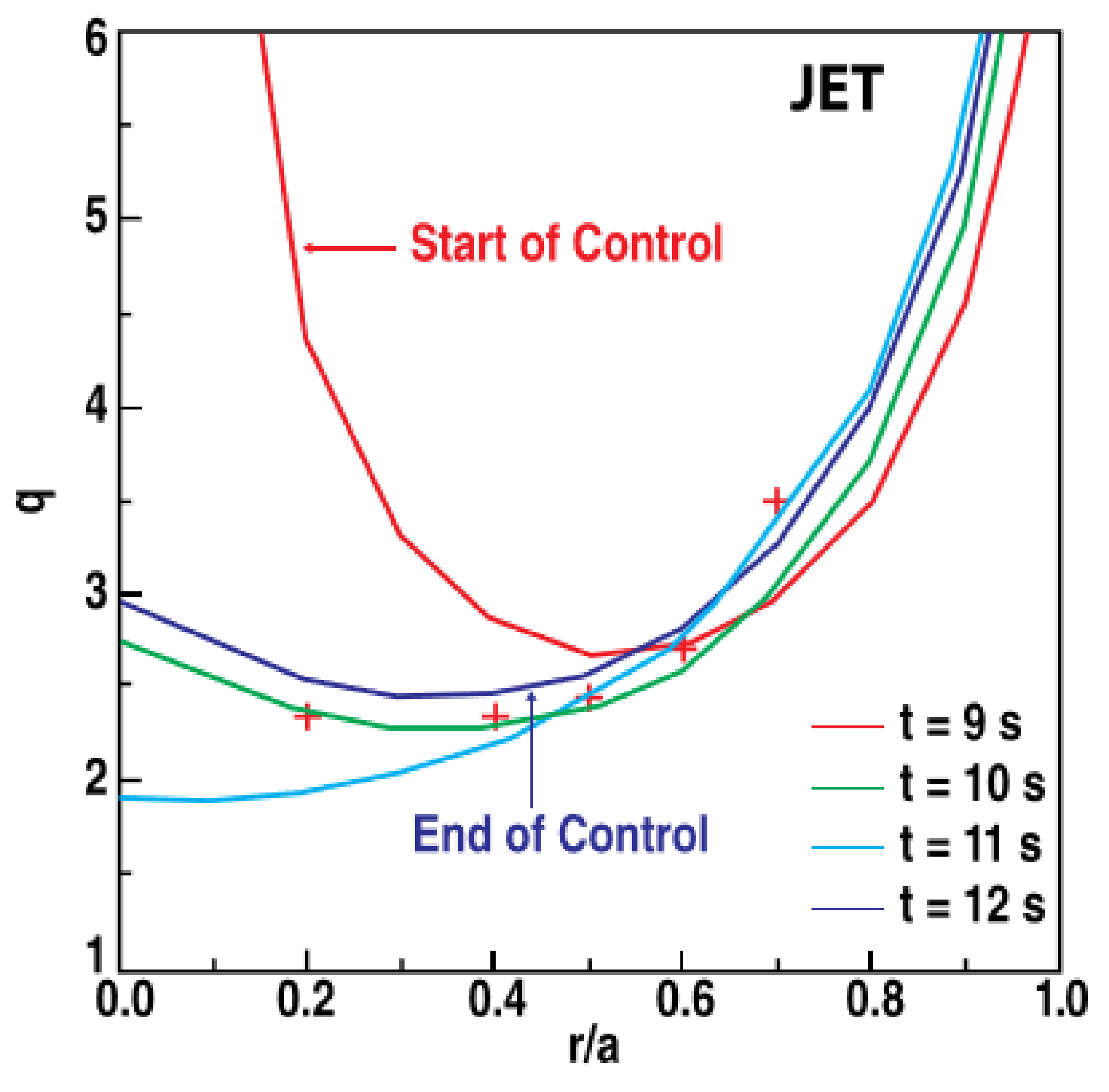
Table 2. ITER plasma kinetics control specifications[1]

Plasma kinetic attribute	Nominal (for ignited or high-Q burn)	Control accuracy (%) (variance during normal operation)	Maximum or minimum
Density (10^{20} m^{-3})	0.7–1.0	±10%	$\lesssim$1.3 ($\cong$1.5n_{GW})
Fusion power (GW)	1.0–1.5	±10%	$\lesssim$1.8 (for 10 s)
Edge/separatrix power (MW)	$\gtrsim$120 (= 1.2P_{L-H})	±20% (?)	$\gtrsim$120 (?)
Divertor power (to target) (MW)	$\lesssim$50	±20% (?)	$\lesssim$100 (steady state) $\lesssim$200 (for ~3 s)
Auxiliary power (MW)	0 (ignited); 0–100 (high-Q driven burn); e.g. 100 MW at Q = 15	0–100 MW as required (dynamic P_{fus} control in ignited plasmas or supplemental P_{fus} control in driven burn plasmas)	$\lesssim$100

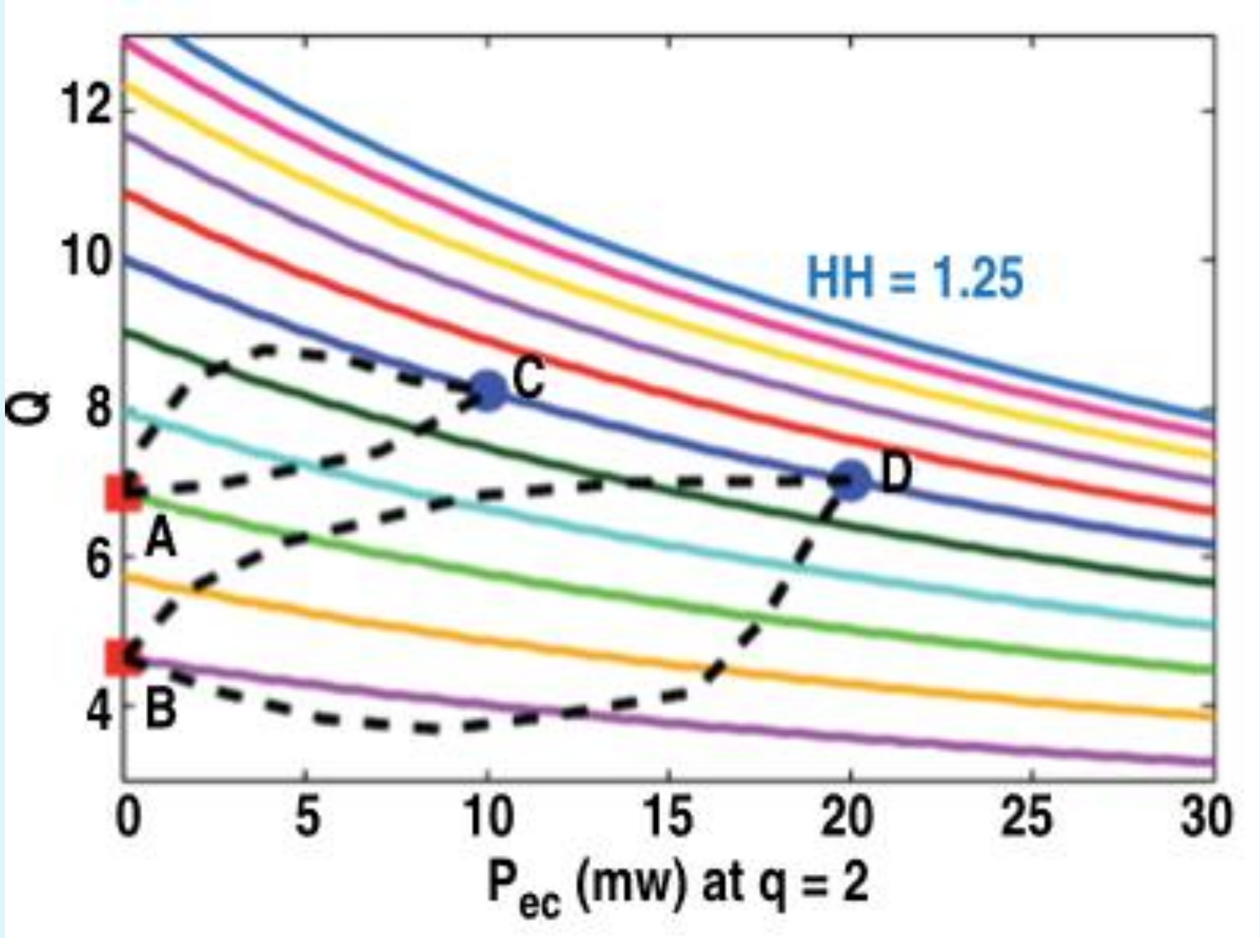
[1]Representative parameters for B = 5.7 T, I = 21 MA, ELMy H-mode energy confinement, ~9% thermal He, 0.2% Ar, 'most likely' L–H power threshold (α = 0, see Section 4.3 of Chapter 2).

Discharge Advanced Control

Physics of Plasmas 22, 021806 (2015)



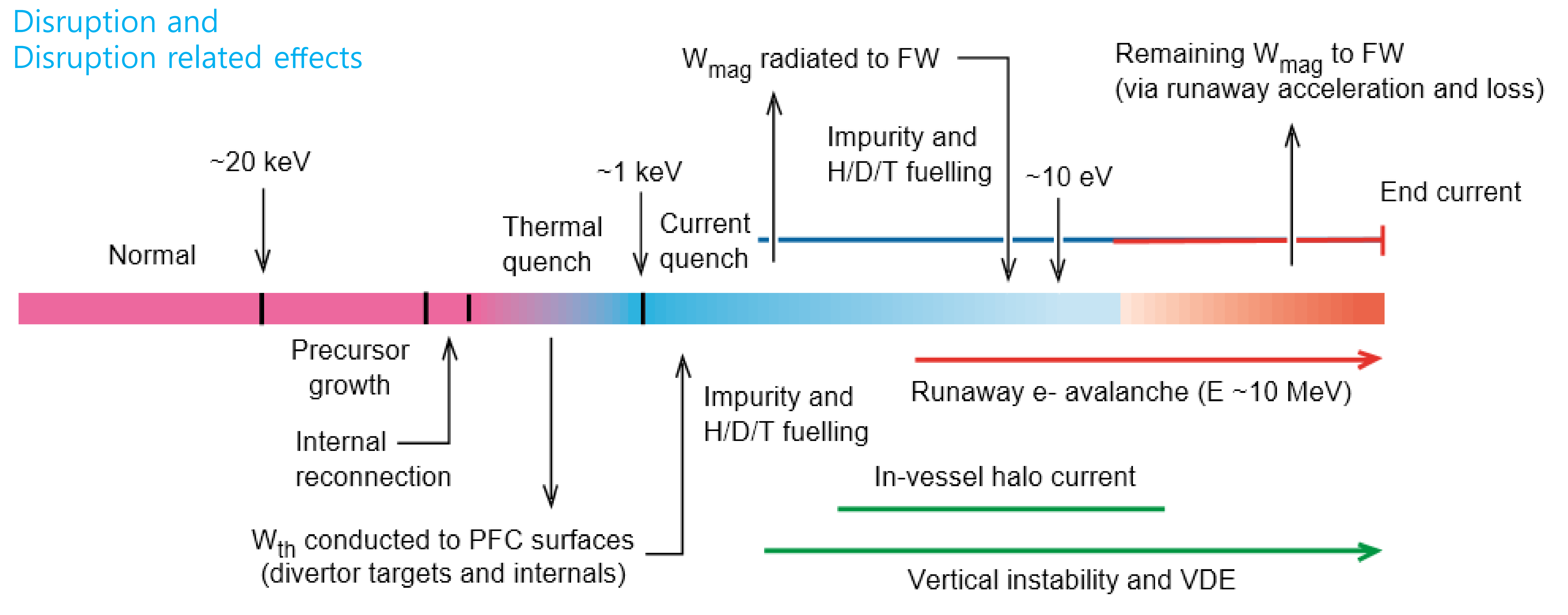
Profile and Stability control



ELM Suppression and Mitigation

Disruption

Nuclear Fusion **39**, No. 12 (1999)



Disruption Causes and Classes in JET

Nucl. Fusion **51**, 053018 (2011)

Type of technical problem	Label
Impurity control problem	IMC
Influx of impurities	IMP
Density control problem	NC
Too much gas from gas injection module	GIM
No (effective) pumped divertor	DIV
Shape control problem	SC
Plasma too close to the wall	WAL
High recycling	RCY
Other real-time control problem	RTC
Emergency shut-down	STOP
Manual emergency stop by operator	SL
Wrong validated density for feedback	PDV
Magnetic signal(s) error	MAG
Reciprocating probe	PRO
Na influx by lithium beam diagnostic	LIB
Other diagnostic problem	DIA
Too little auxiliary power	AUX
Too little torque/rotation	ROT
Problem with neutral beam injection	NBI
Impurity release due to LHCD	LHC
Impurities from ICRH antennae	ICH
Problem with vertical stability control	VS
(Intentional) vertical kink	VSK
Temperature too high in VS amplifier	VST
Over-current in VS amplifier	VSI
Other failure of VS amplifier	VSA
Human error	HUM
Too fast a current ramp-up	IP
Other power supply problem	PS
Unidentified impurity influx (flying object)	UFO
Problems due to pellet injection	PEL
Impurity influx by laser ablation	ABL
No clear cause	NON

Type of physics problem	Label
General (rotating) $n = 1$ or 2 MHD	MHD
Mode lock	ML
Low q or $q_{95} \sim 2$	LOQ
Edge q close to rational (>2)	QED
Large sawtooth crash	SAW
Neo-classical tearing mode	NTM
Internal kink mode	KNK
Reconnection	REC
Radiative collapse ($P_{rad} > P_{in}$)	RC
MARFE	MAR
Greenwald limit (n_{GW})	GWL
High density operation (near n_{GW})	HD
Too low density (and low q)	LON
H-to-L back-transition	HL
Strong density peaking	NPK
Too strong internal transport barrier (ITB)	ITB
Strong pressure profile peaking	PRP
Negative central magnetic shear	MSH
Large edge localized mode (ELM)	ELM
Vertical displacement event	VDE

JET disruption classes			%
Impurity (control problems)	IMC		18.7
Density control problems	NC		15.6
Auxiliary power shut-down (H–L)	ASD	0.04–0.8 s	10.0
Fast emergency shut-down	FSD	0.1->2 s	9.6
Neo-classical tearing mode	NTM	0.1->2 s	8.2
Shape control problems	SC		6.0
Current ramp-up	IPR		5.9
(Low density) error field mode	EFM	0.1–1 s	5.6
Strong internal transport barrier	ITB	0.01–0.05 s	5.1
Vertical stability control problem	VSC	0.02–0.1 s	4.6
Greenwald limit	GWL	0.05–0.8 s	2.4
No clear classification			8.2

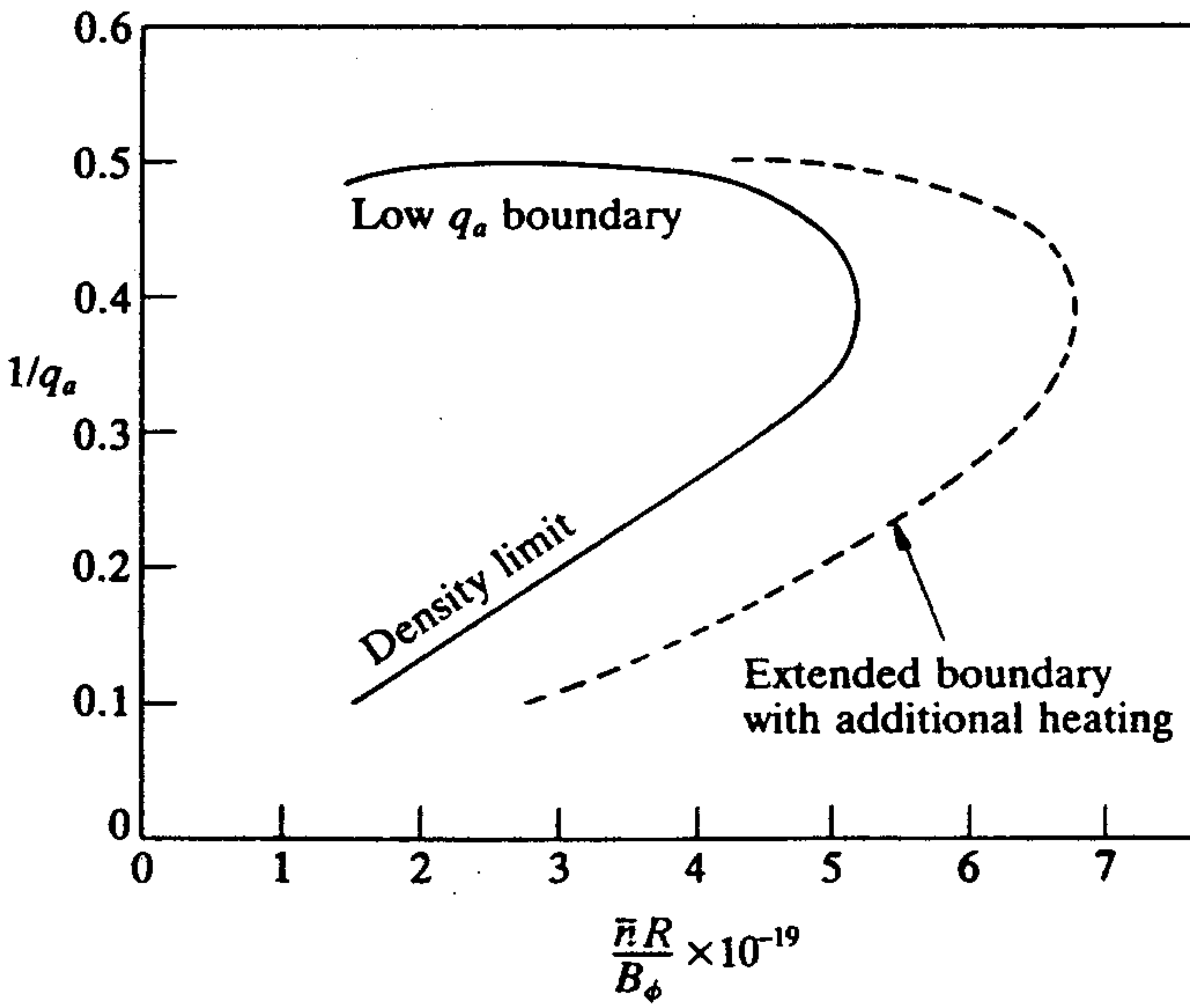
Two Major Causes of Disruptions

- Low-q disruptions
  (LOQ, QED)
- Density limit disruptions
  (LON, GWL, RC, MAR, HD)

Greenwald density limit
$n_{GW}(10^{20}\ m^{-3})=I(MA)/a^2(m)$

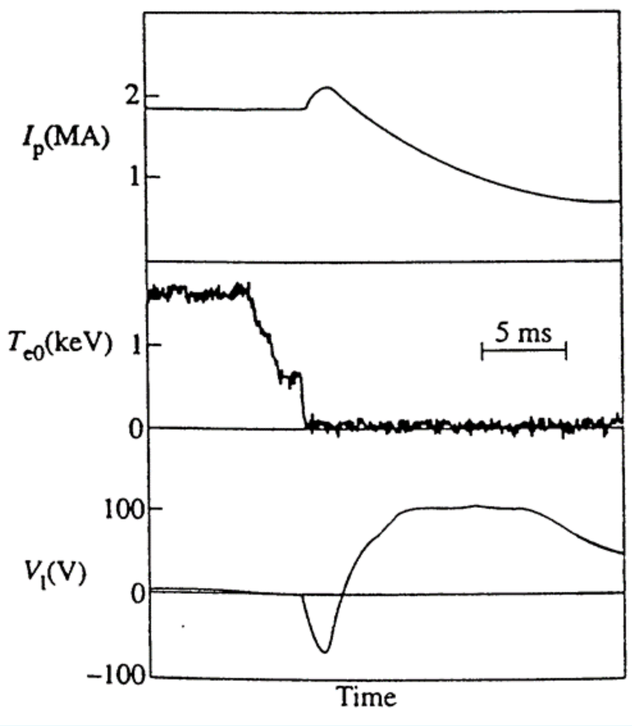
Troyon normalized beta
$\beta_N = <\beta(\%)> I(MA)/a(m)B(T)$

($q_\psi \approx 2$, $n/n_{GW} \approx 1$ and $\beta_N \approx 3.5$)



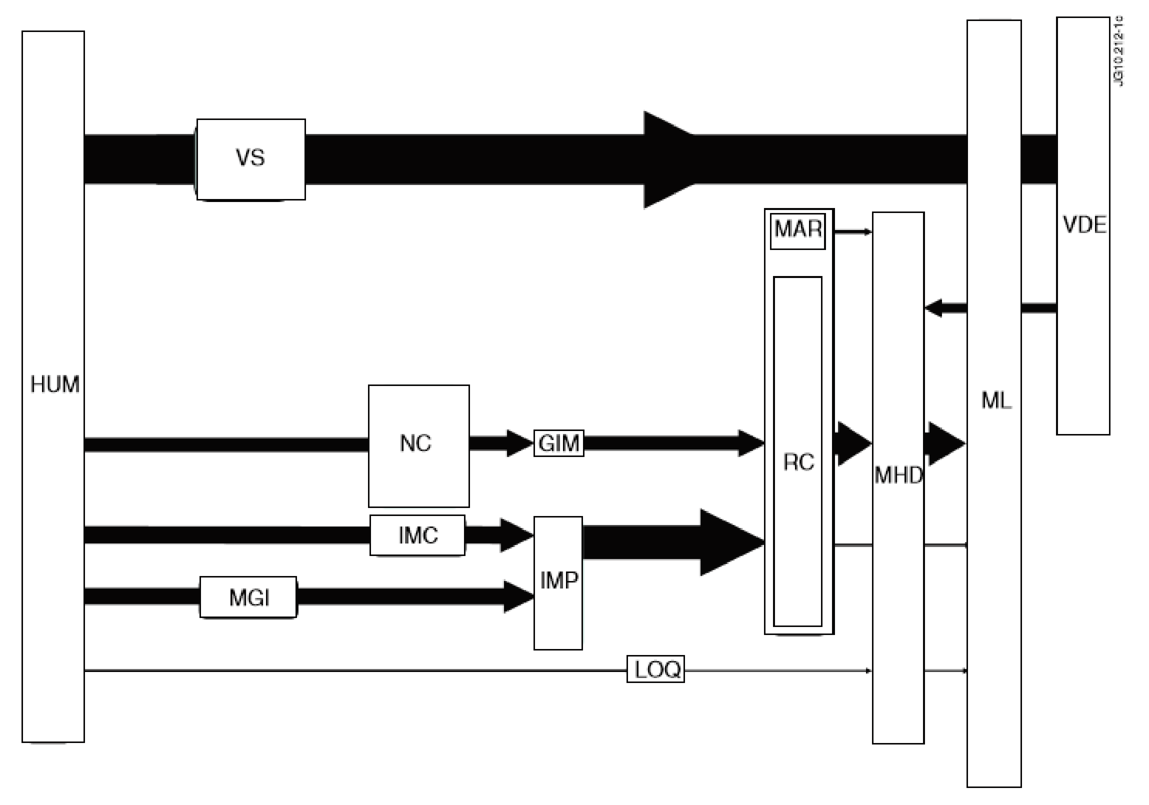
Two Major Disruptions
from non-linear evolution of ideal MHD

- Disruption by long wavelength, non-axisymmetric MHD instabilities
  - Various onset causes may be initiated
  - thermal energy is lost first in the thermal quench phase
  - current density profile flattens
  - internal inductance is reduced resultantly
  - total plasma current increases
  - current quench occurs from the cold plasma



- Vertical Displacement Events (VDE)
  - the plasma moves vertically to strike the material wall
  - thermal quench occurs followed by a current quench without an increase in the current

Schematic Sequence of Disruption Events

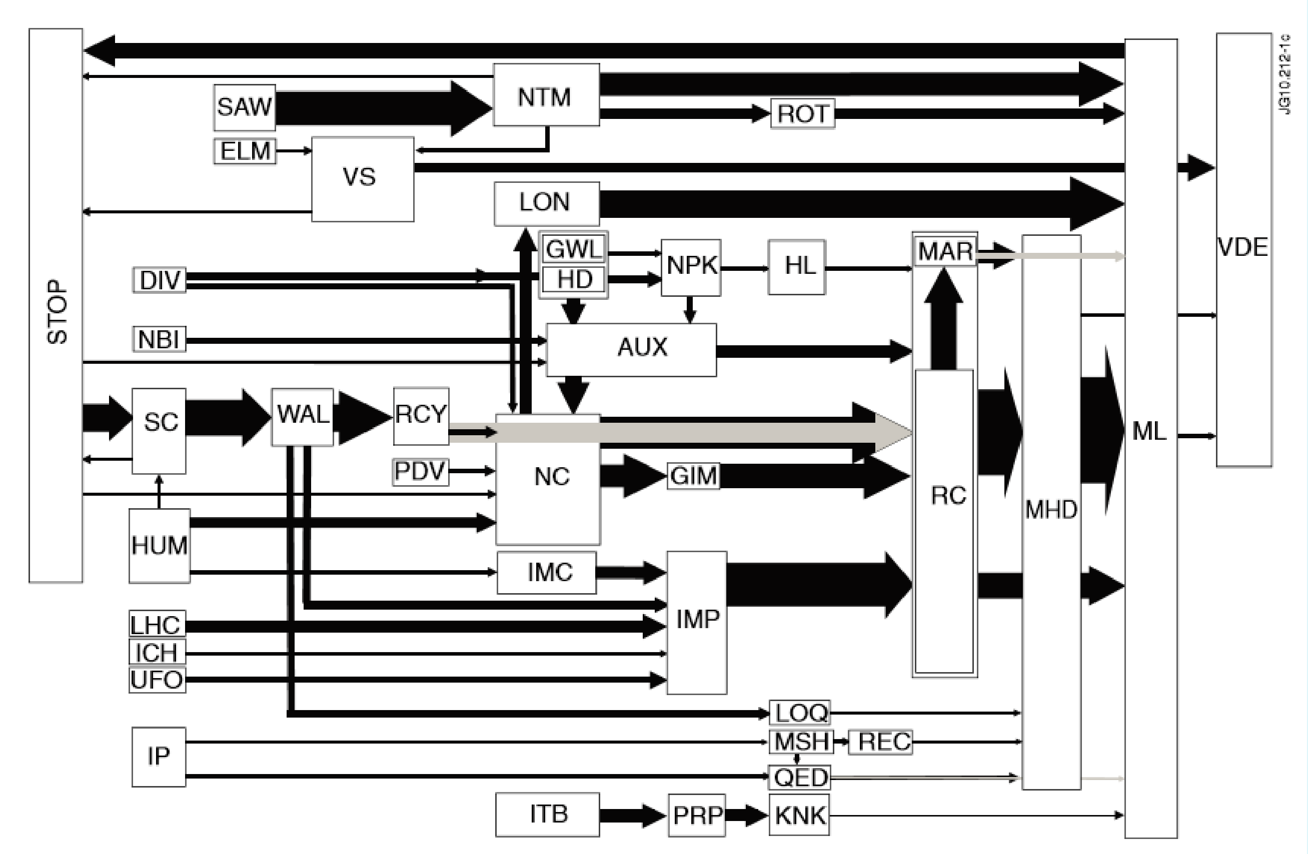


Intentional disruptions

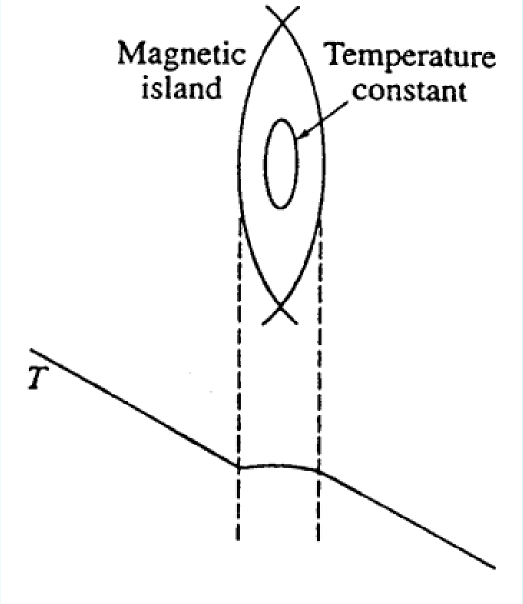
- VS → VDE (→ MHD → ML)
- NC (GIM) → MAR/RC → MHD → ML
- IMC/MGI → IMP → RC → MHD → ML
- LOQ → MHD → ML

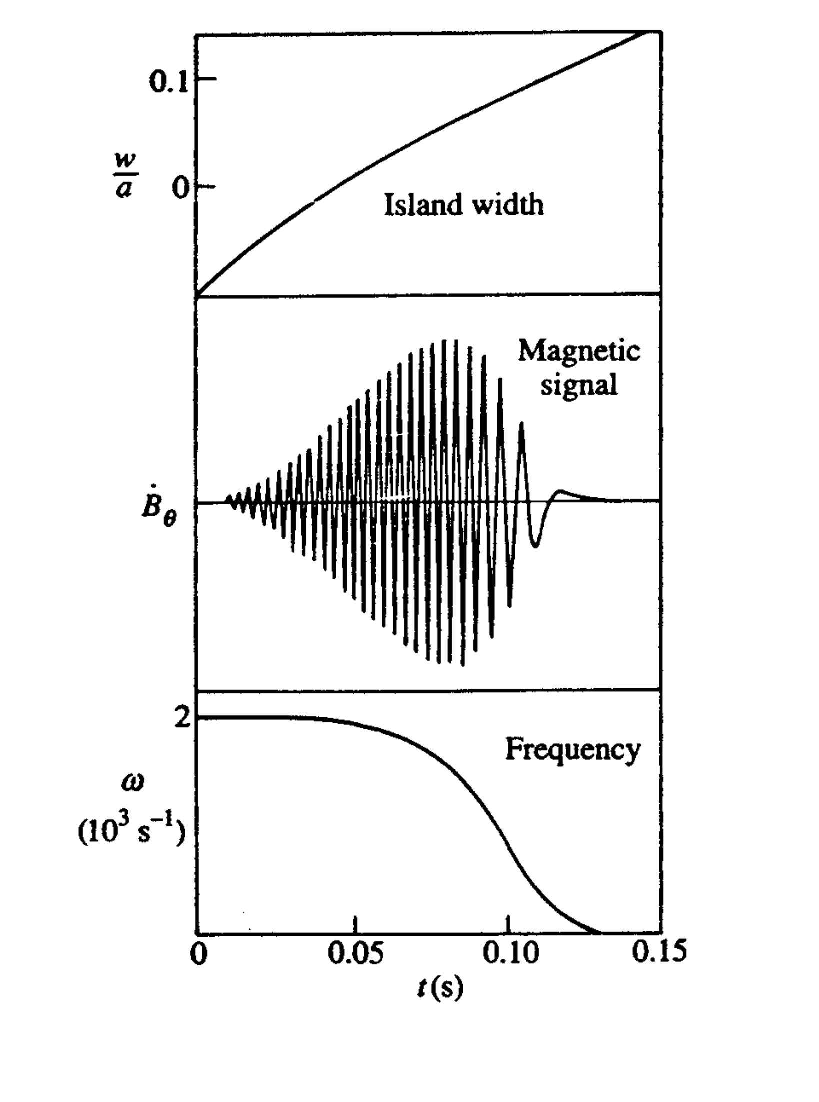
Unintentional disruptions

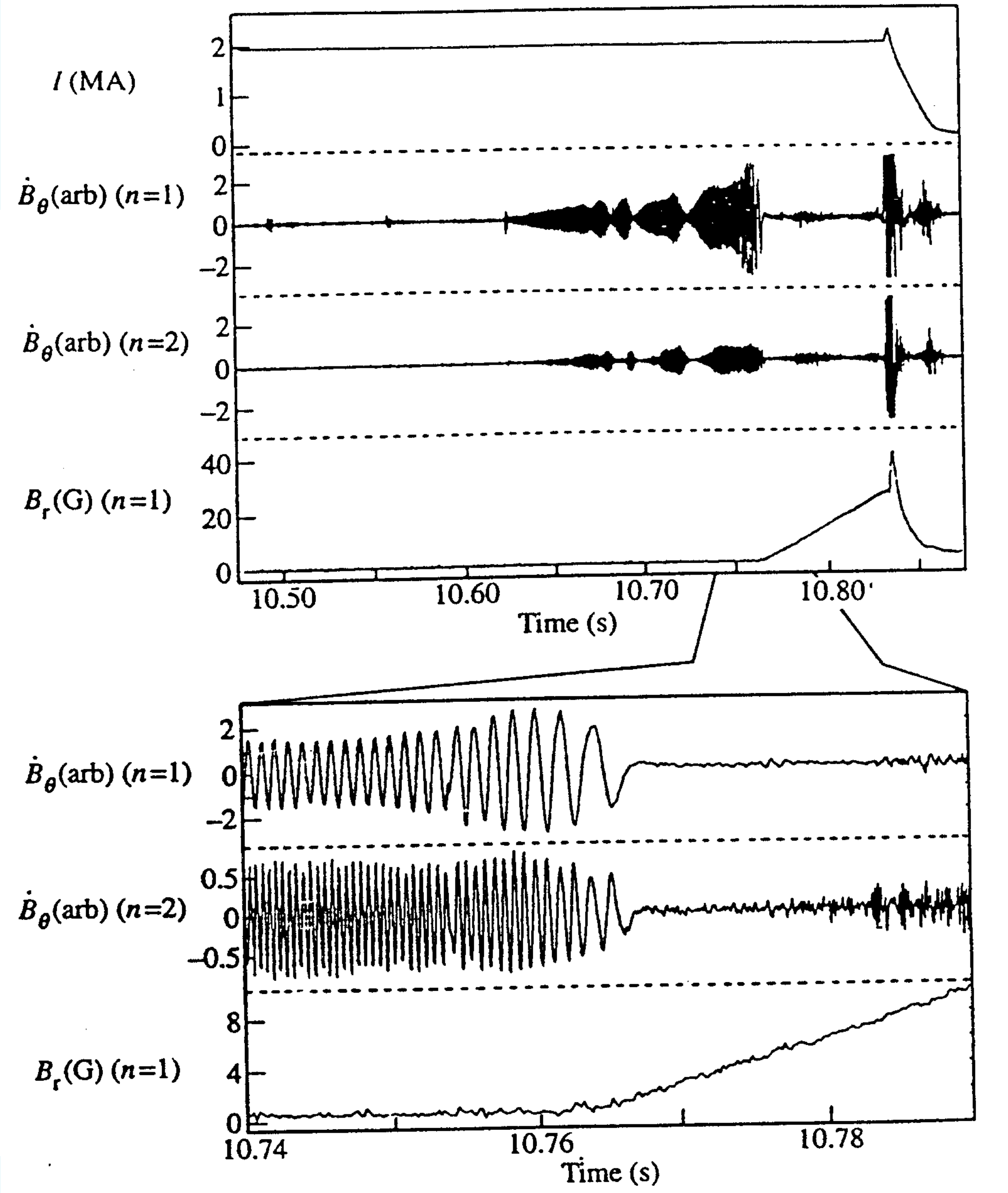
- VS → VDE
- … → MAR/RC → MHD → ML (→ VDE)
- … → LON/LOQ/QED/REC → MHD → ML
- SAW/ELM → NTM (→ ROT) → ML
- ITB → PRP → KNK → ML



MHD and Mode Locking

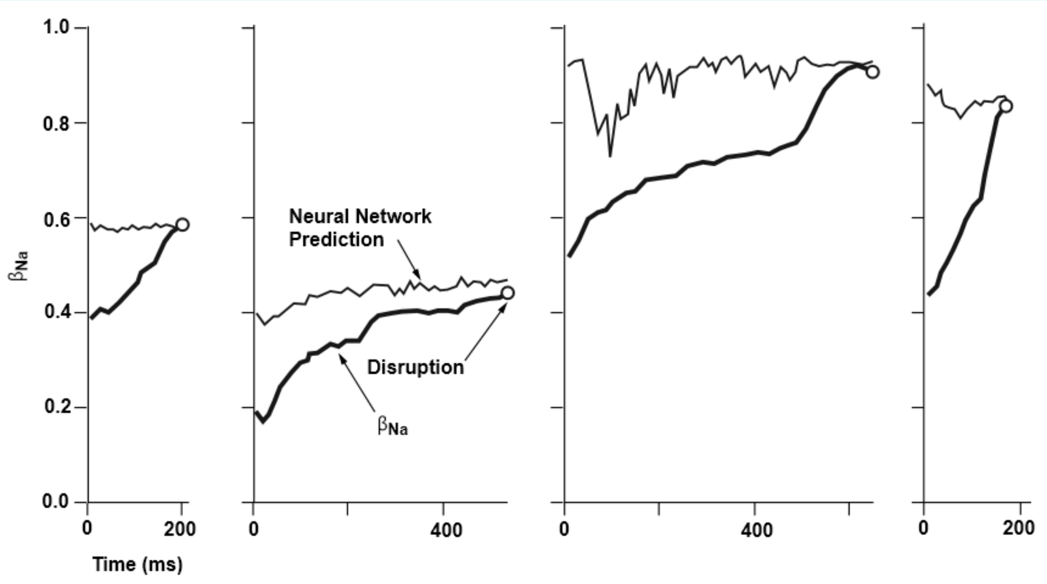


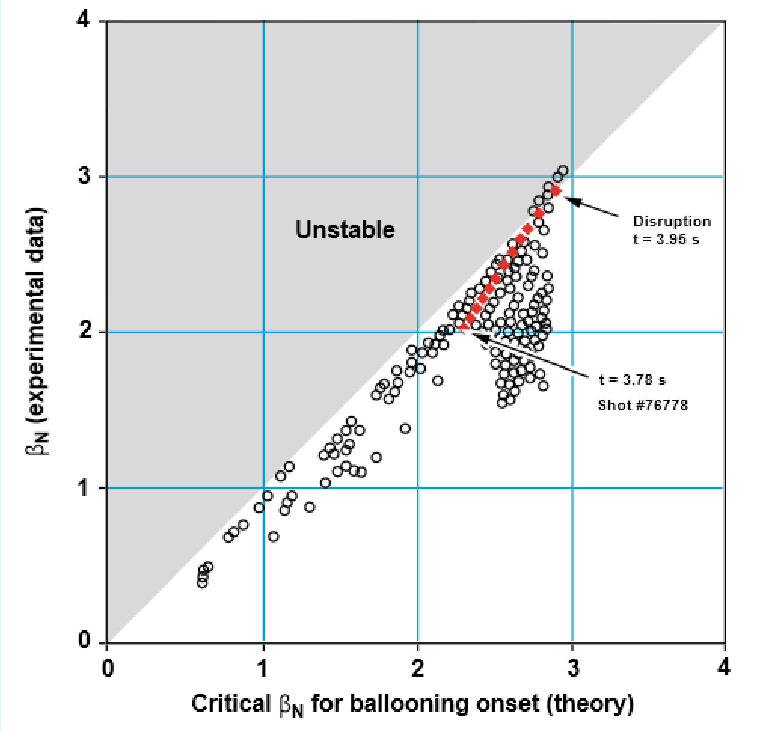




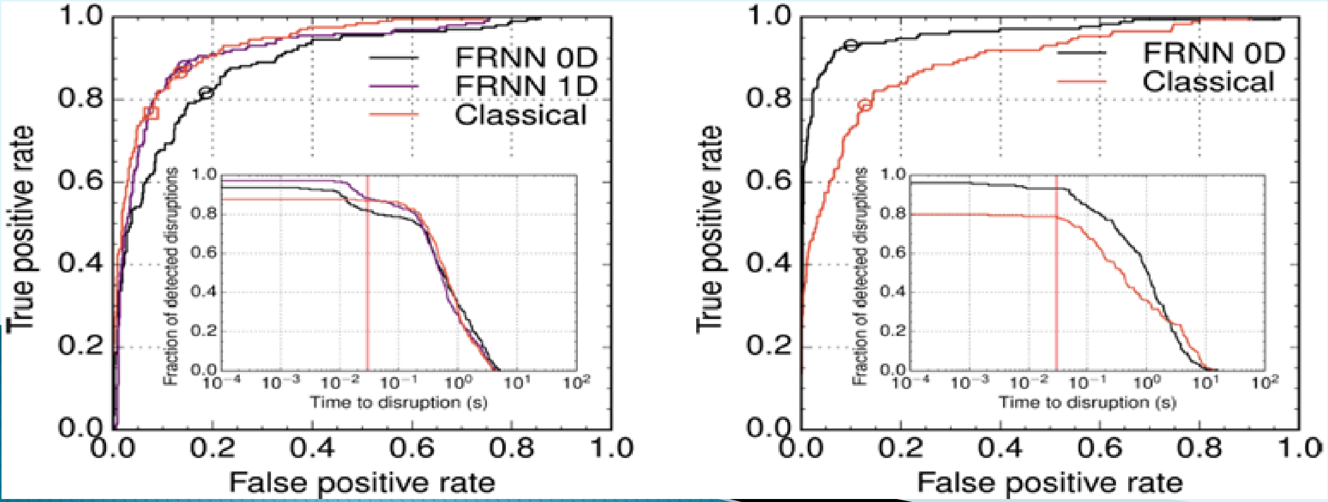
Disruption Prediction

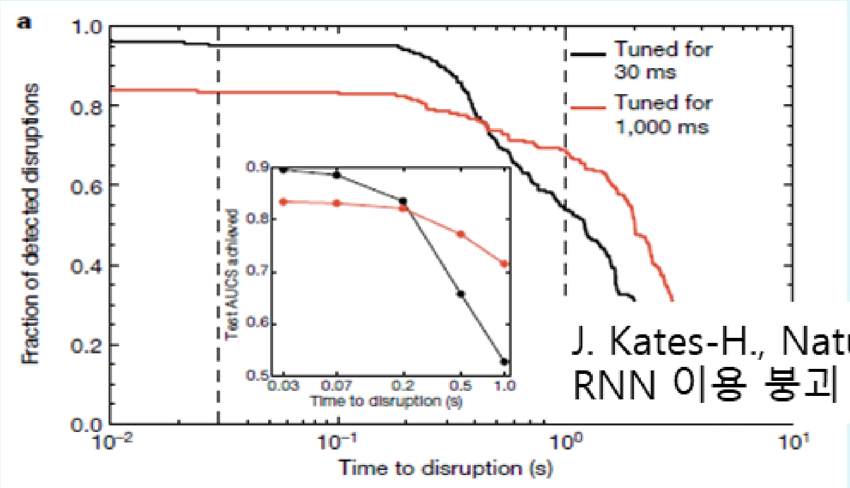
Neural network disruption prediction in DIII-D





'Prediction' of a beta limit disruption in TFTR

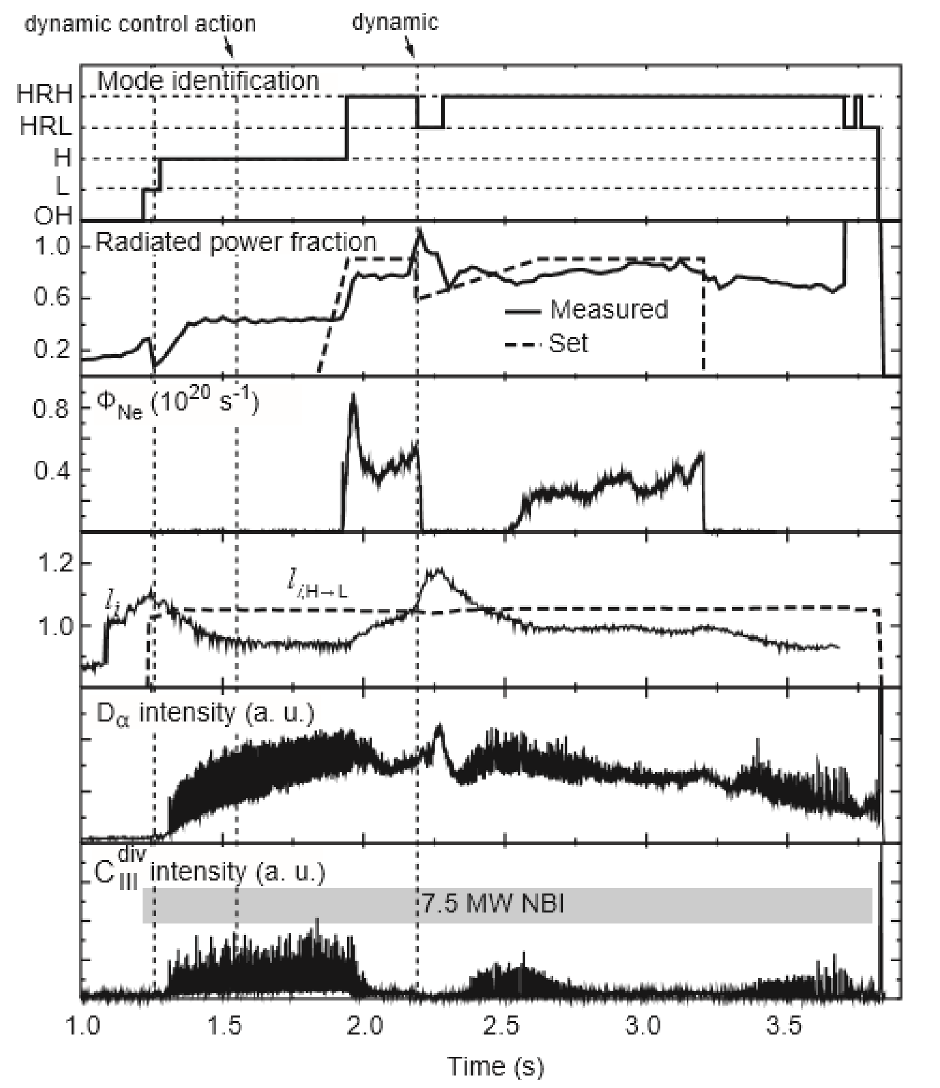




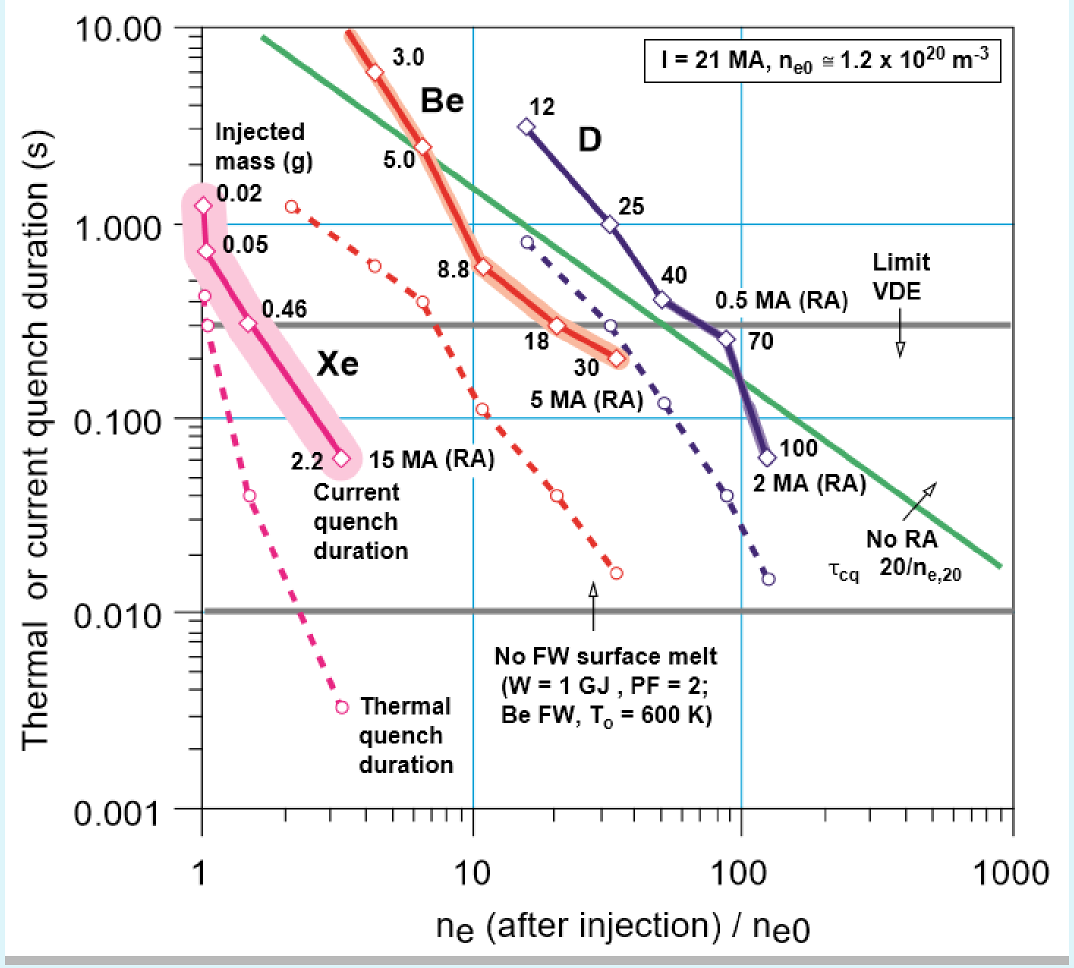
J. Kates-H., Nature '19

RNN 이용 붕괴 예측 사전연구

Disruption Avoidance and Mitigation



Disruption avoidance in ASDEX-U : upon detection of loss of HRH mode (high radiation H-mode)



Thermal and current quench durations for fast plasma shutdown in ITER with various quantities (masses in g) and species of injected impurity