Necessary Diagnostics

Interferometer

- Plasma density is a crucial operating parameter
  - key parameter defining stable operation window
  - strongly affects OH confinement
  - strongly affects RF wave access (ECRH, LHH, AWH…)
  - strongly affects Neutral Beam shine-through
  - strong coupling to edge physics
    - high density, low $T_e(a)$ ™ low sputtering yields
- Design considerations
  - wavelength
    - avoid refraction losses near OM cut-off
    - avoid vibration problems when wavelength too short
  - geometry
    - vertical (easier to make vibration-proof)
    - mid-plane (insensitive to plasma radial position)

Necessary Diagnostics

Interferometer

- Profile relationships

  - If $n = n_0 \left(1 - (r/a)^2 \right)^{\alpha}$

    typically with $0.5 < \alpha < 2$

    then

  - $n_0 / \bar{n} \approx \bar{n} / \langle n \rangle \approx \sqrt{(1 + \alpha)}$

  - To raise α :
    - run at low density (high I/N)
    - use deep-fuelling pellet injection
    - reduce edge recycling (e.g. helium GDC between shots)

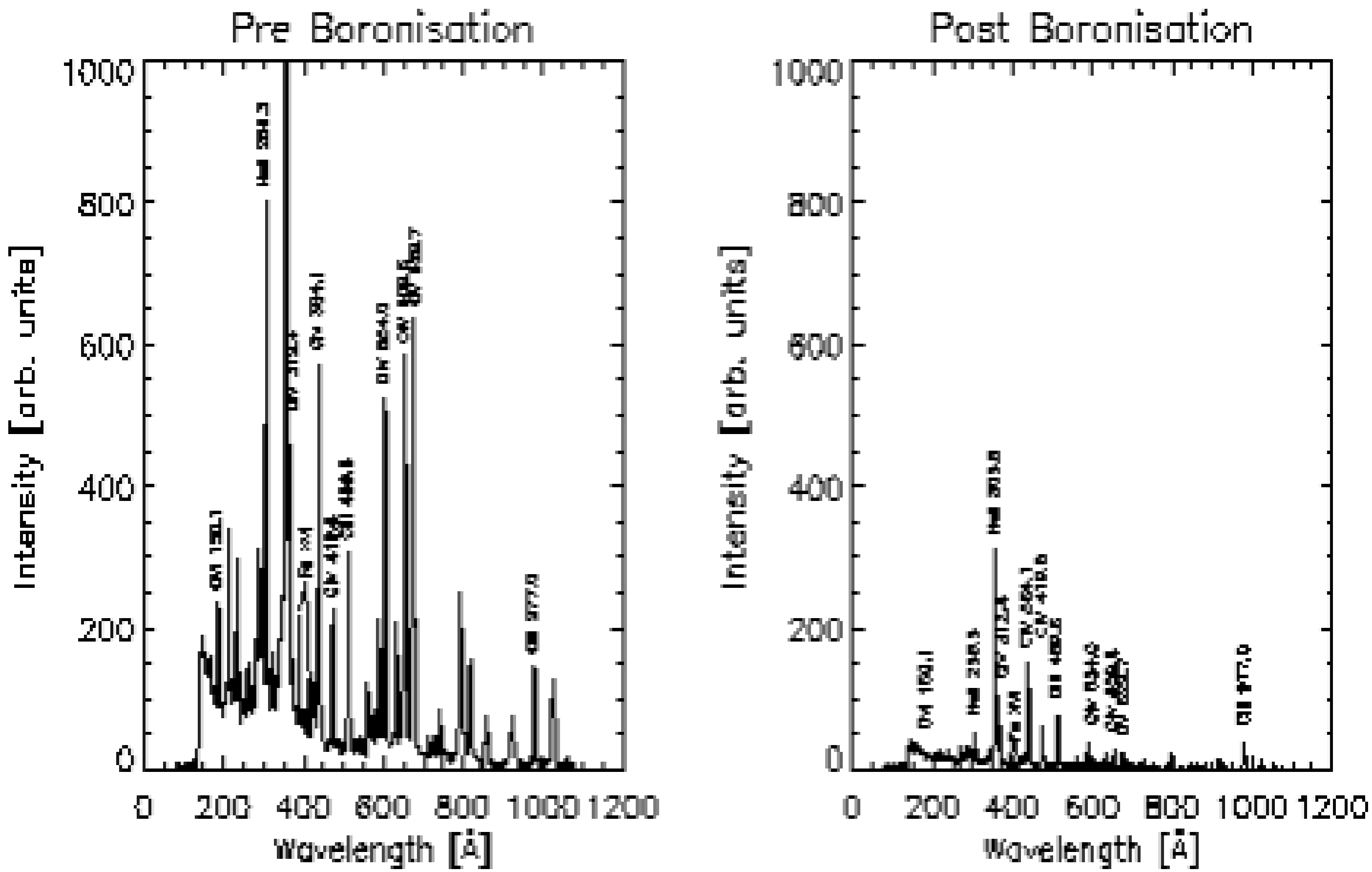
Necessary Diagnostics

Impurity survey spectrometry

- Facilitates operational improvements
  - identify dominant impurities
  - identify operational problems
    - “strange” materials e.g. Langmuir probes, forgotten tools
    - poor vacuum cleanliness
    - insufficiently conditioned limiter surfaces
  - corroborate data on T_e (ionisation stage burn-through)
    - spatial profile helps deduce $T_e(r)$
    - care with validity of coronal equilibrium assumption

Necessary Diagnostics

Impurity survey spectrometer (COMPASS-D)



Results from SPRED VUV Spectrometer
H. Meyer, I Lehane

Plasma Initiation

Stray magnetic fields

- Non-resonant, or toroidal average B_θ
  - causes toroidal magnetic field lines to spiral across the vessel
  - accelerates losses of initial electrons from the vessel
  - inhibits electron avalanche
  - inhibits flux surface closure at low plasma current
    - so design in a poloidal field null region...
      .. in theory m≥4 but in practice m=2 is OK

- Resonant, i.e. with pseudo-helical components
  - can cause tearing mode locking during current rise phase
    - possible early disruption
    - probable waste of volt-secs
  - sources include
    - feeder bar stray fields (especially with jointed TF coils)
    - zones of high magnetic permeability in or near the torus

Plasma Initiation

Stray magnetic fields (ITER)

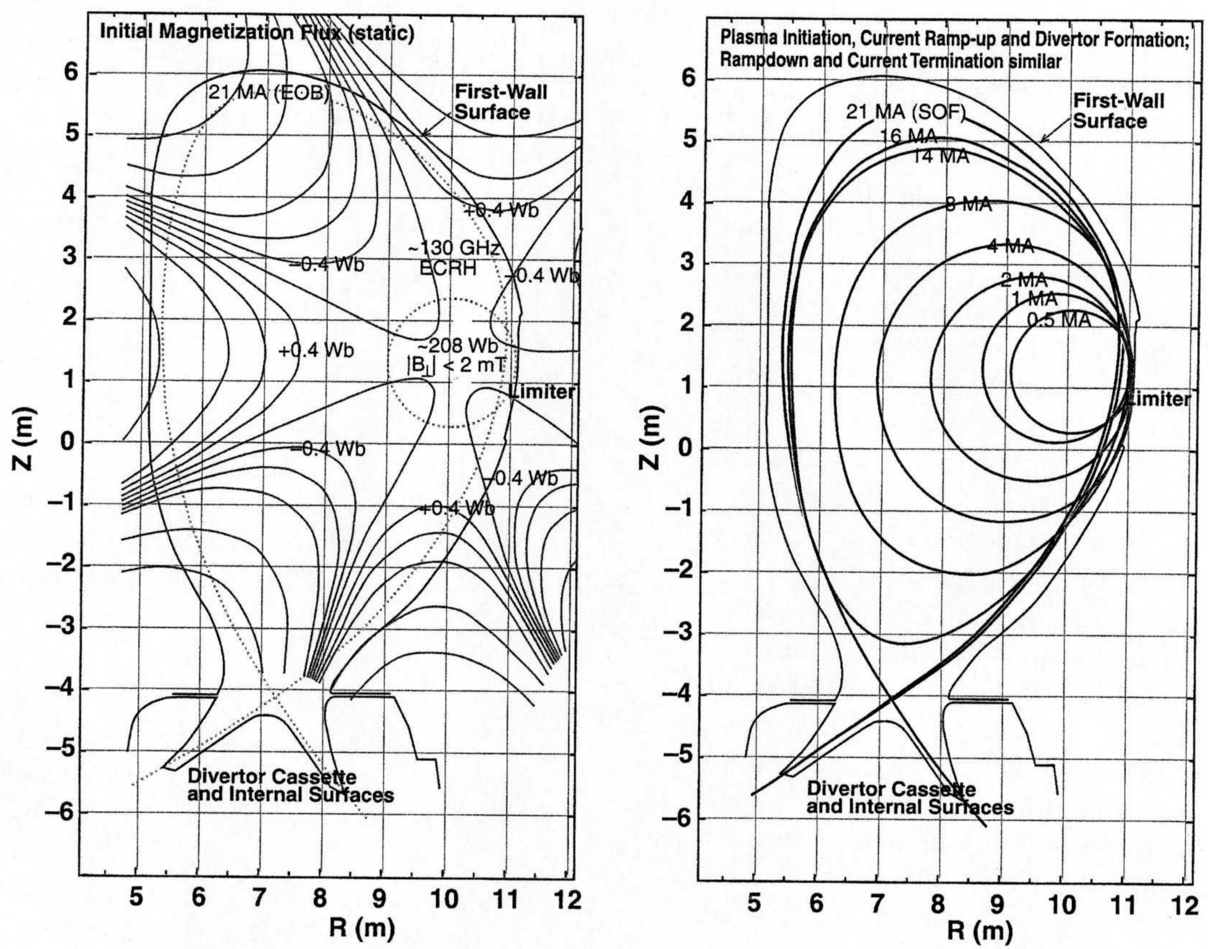


Figure 13. Plasma initiation and current ramp up configurations in ITER (Ref. [103]).

NB octupole structure of null

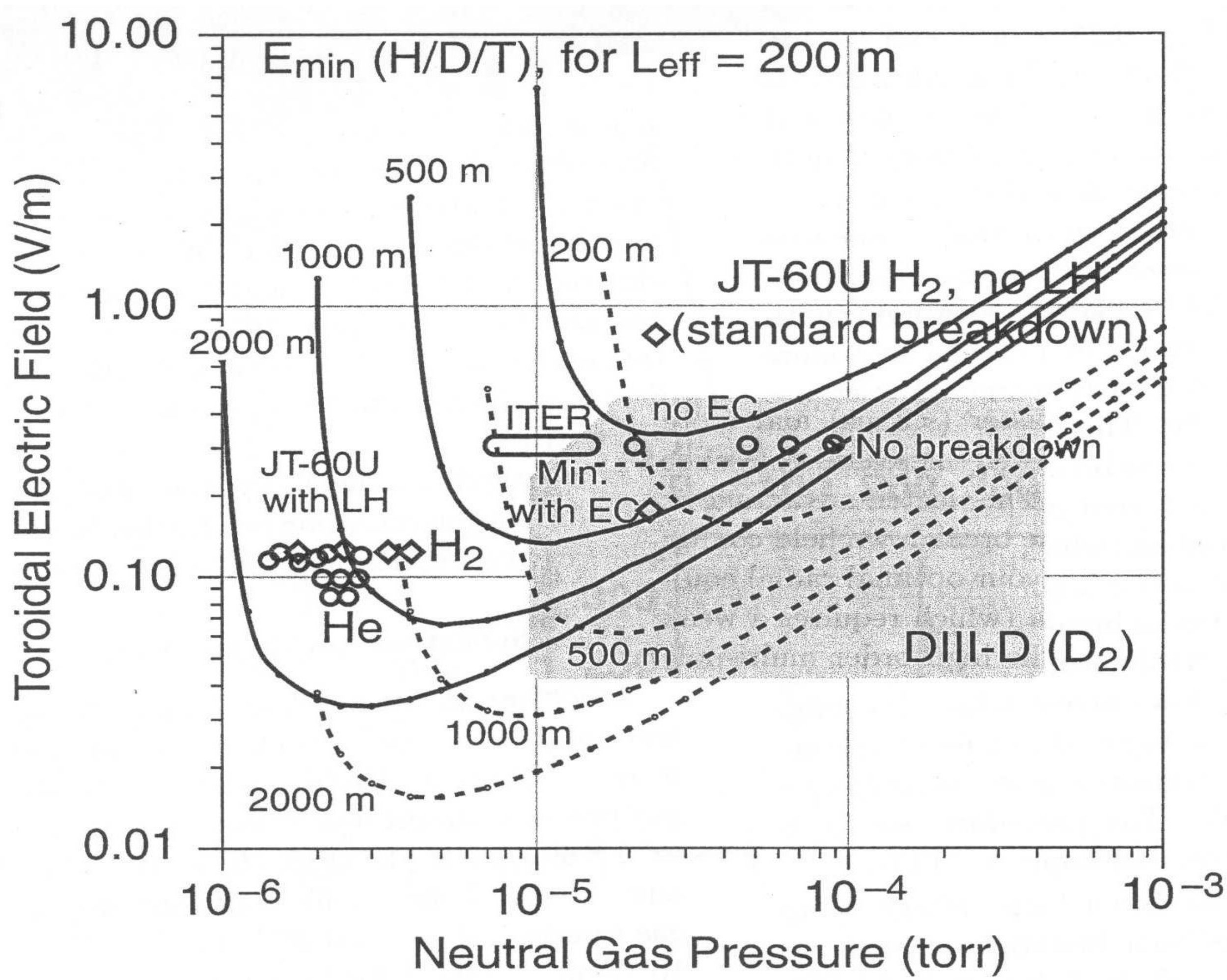
Gas breakdown and current rise

- Gas breakdown is a classical Pashen curve phenomenon
  - choose a prefill pressure around 10^{-4} torr
  - produce a toroidal electric field of about 3V/m
  - keep stray $B_\theta / B_\Phi < 10^{-4}$ to avoid prompt electron loss
  - wait 1-3msecs

- Preionisation options
  - UV lamp (not very effective)
  - electron gun
    - ensure electron ∇B drift is into torus from gun location
    - check emission current daily
  - ECRH
    - <10kW is OK
    - care with impurity production where resonance impacts vessel surfaces
  - Reverse plasma current pulse, laser-pellet, radioactive source….

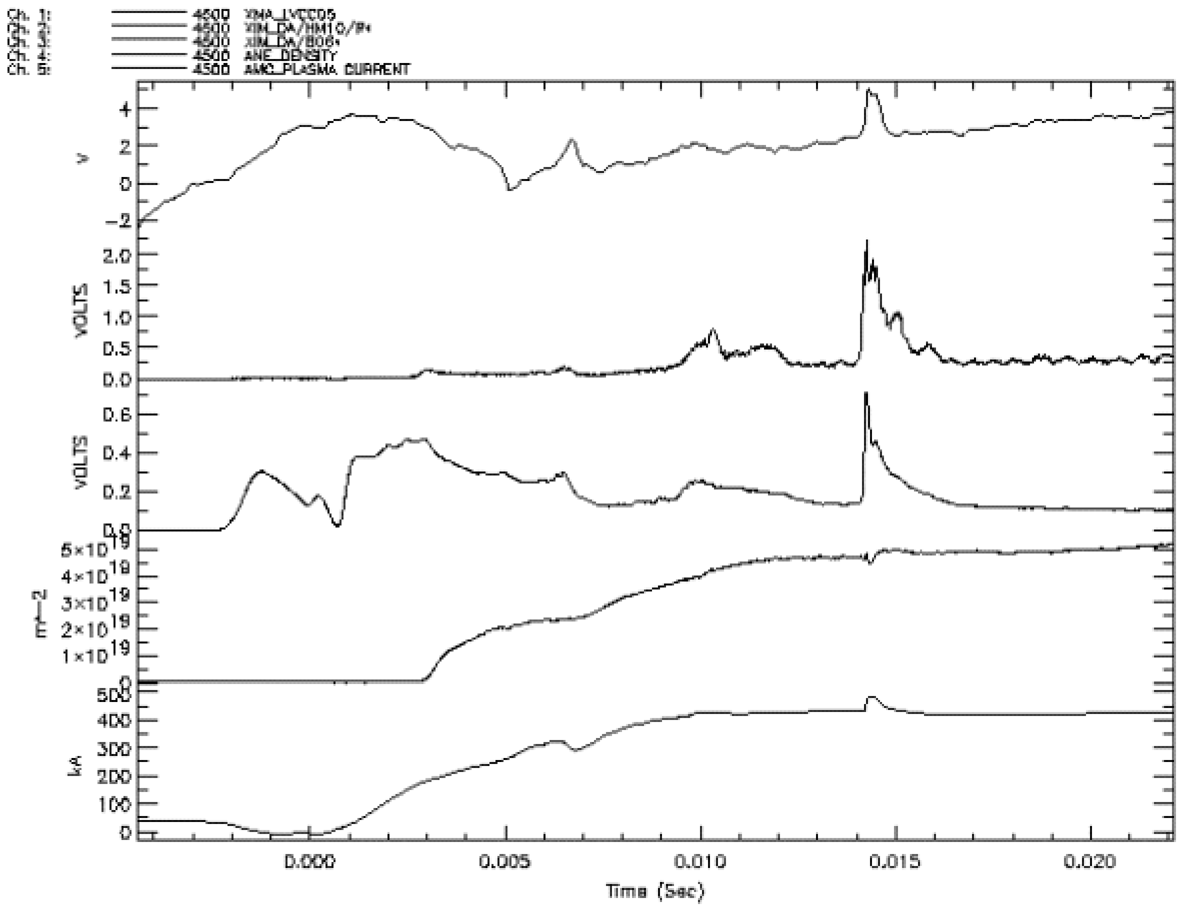
Plasma Initiation

Gas break-down



Plasma Initiation

Gas breakdown (MAST)



V_{loop}

D_{α}-mid

D_{α}-div

density

I_p

UKAEA Fusion

Plasma Operating Limits

Current

- Maximum plasma current is limited by n=1 gross MHD instabilities
  - kink modes
  - tearing modes
  - usually m=3, m=2, coupled m=1 and m=2
  - these are driven by current gradients at the plasma edge and hence resonate with the edge safety factor q_a (or q_{95} in a discharge defined by a magnetic separatrix)

    – $q_a \approx 5a^2 B_\phi (1 + \kappa^2) / 2RI_p$

    – but you need to do an equilibrium code run for accuracy!

- Minimum plasma current is limited by the need to:
  - support the charge exchange and radiative losses
  - confine "fast" ions (eg tail of thermal distribution)
  - provide adequate energy confinement time

Plasma Operating Limits

Current

- Current magnitude sets density limit, as I/N or Greenwald scaling
  - Not really $I_p / (\pi \, n_e a^2)$ but $(\langle j \rangle / n_e)^2$
  - Arises due to OH and P_{rad} having similar $f(T_e, Z_{eff})$

$$P_{OH}/P_{rad} \approx \langle j \rangle^2 Z_{eff} T_e^{-3/2} / n_e^2 f(Z_{eff}) T_e^{\approx -3/2}$$

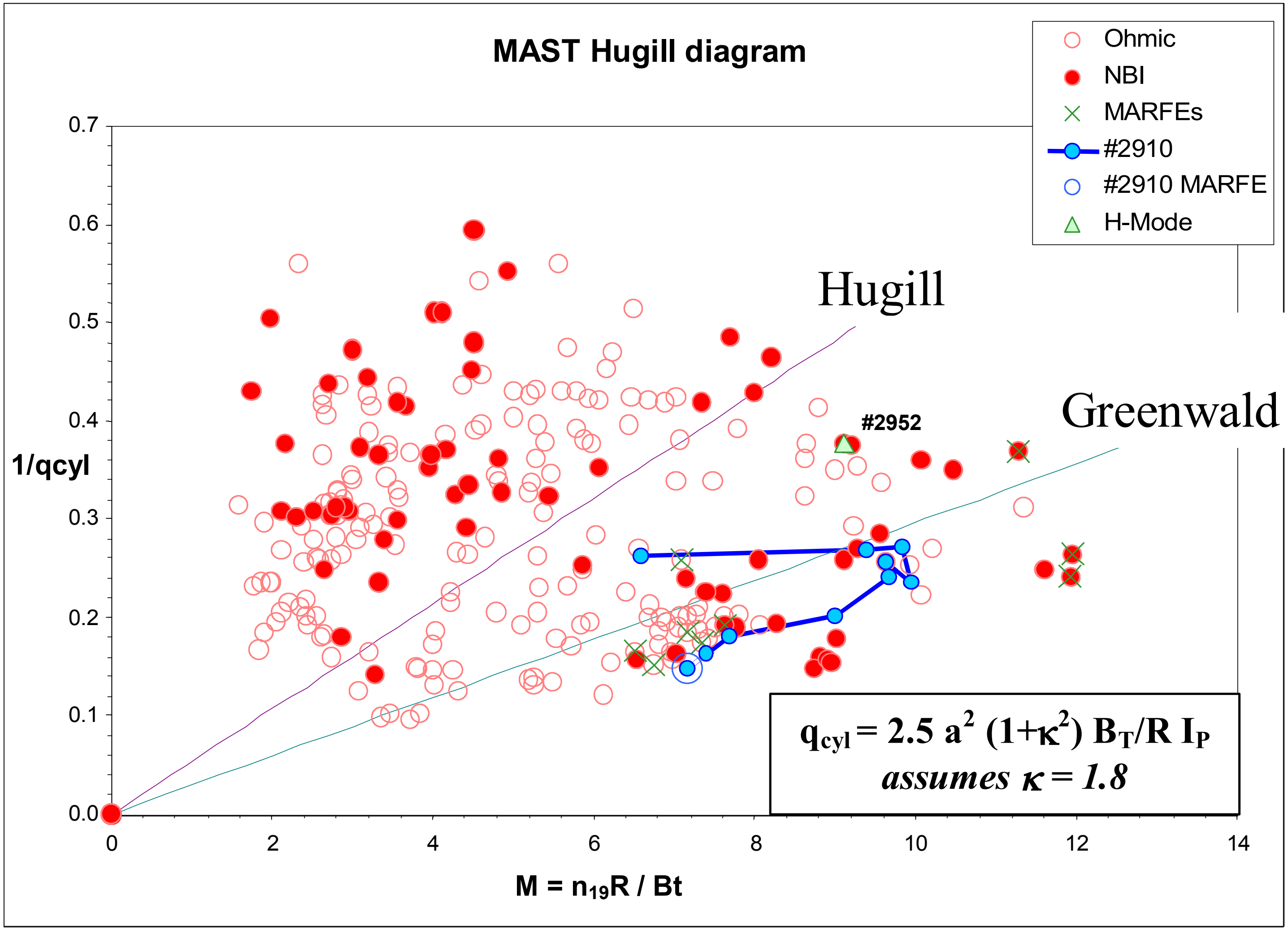
  - Hence an indicator of bulk radiative cooling becoming too large
  - Works for all OH plasma devices between ≈20eV and ≈3keV
  - In tokamaks, radiated power erodes plasma current channel and destabilises the m=3 or m=2 mode.
  - Reduction of Z_{eff} does help expand operating limits

Plasma Operating Limits

Density

- Maximum density is set by disruptive limit, raised by:
  - better vessel conditioning
  - limiter conditioning
  - low-Z vessel and limiter coatings
  - pure hydrogenic pellet injection
    - reduces Z_{eff}
    - raises density profile peaking factor (α)
  - increased auxiliary heating power (if Z_{eff} is kept low)
- Minimum density is set by electron slide-away condition
  - toroidal electric field accelerates all electrons, tail electrons become collisionless if density is too low
    - keep E_{ϕ} small (helped by clean machine)
    - keep $I/N < 1.5 \times 10^{-13}$ amp-metres
- Consider also the needs of the auxiliary heating system
    - sufficient line density to absorb neutral beam
    - RF wave access

Plasma Operating Limits



$q_{cyl} = 2.5\ a^2\ (1+\kappa^2)\ B_T/R\ I_P$

assumes $\kappa = 1.8$

Plasma Operating Limits

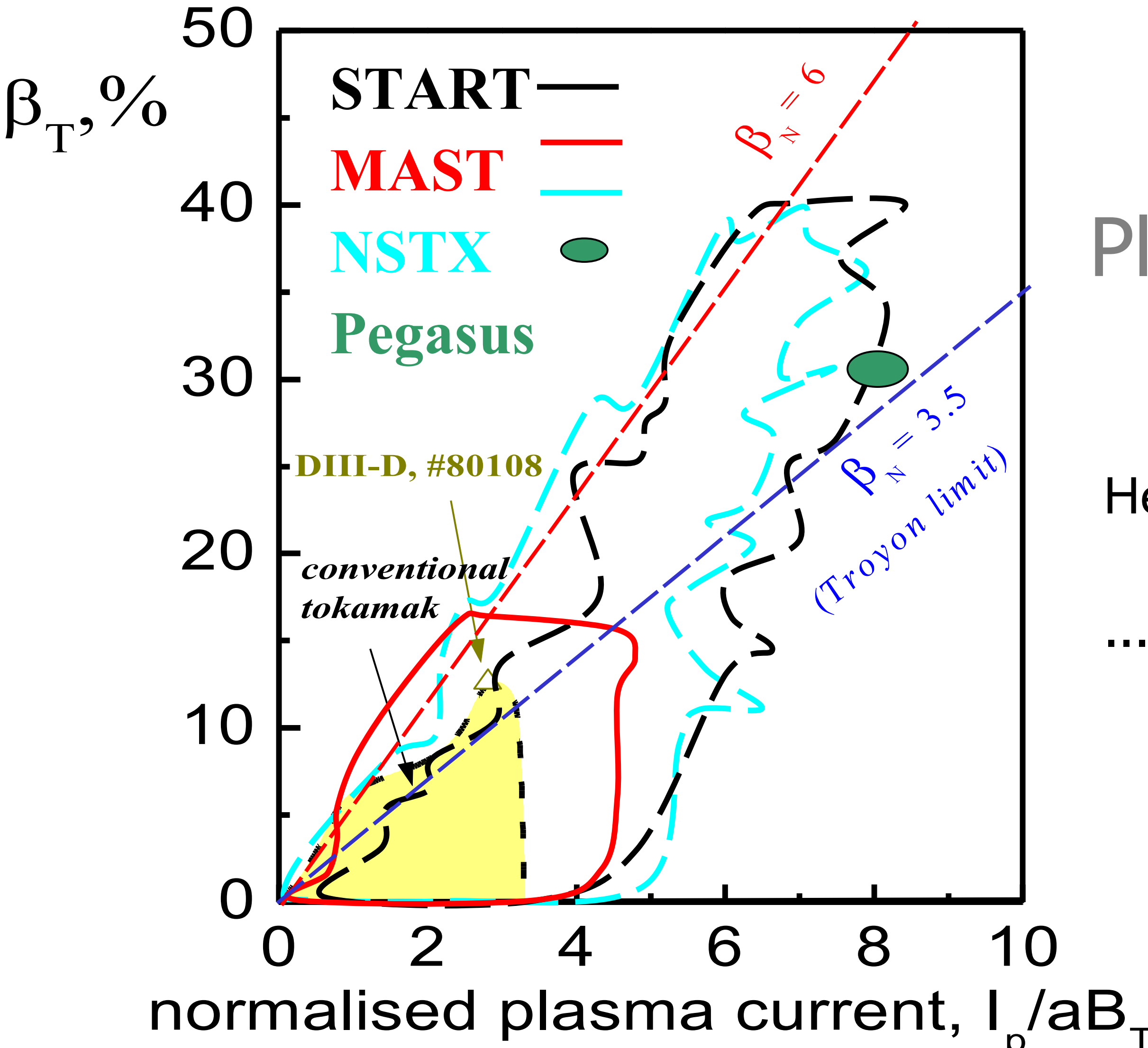
Pressure

- Plasma pressure has no lower limit
- The upper limit is set by β, i.e normalised to magnetic field pressure.
  - Ideal kink modes set low-m limits
    - require $q_0 > 1$ (not generally true!)
    - most constraining when $q_a \approx$ integer
  - Ideal ballooning modes set high-m limits
    - actually limited by FLR effects to m<30
    - "ballooning" means "ballooning the flux surface perturbation outwards in regions of poor magnetic curvature"
  - Both have similar parametric dependence:

    $\beta \approx 4\, I_p / a\, B_\phi$ (%, MA, m, Tesla) or equivalently

    $\beta \approx 20 \varepsilon \kappa / q_a$ (%, dimensionless) where $\varepsilon = a/R$
  - Both have resistive analogues with lower thresholds and non-linear saturation effects clamping achievable pressure

Plasma Operating Limits



Plasma pressure (MAST)

Here, $\beta_T = \langle p\rangle/(B_{\phi o}{}^2/2\mu_o)$

...but Troyon used:

$\langle p\rangle/\langle B^2/2\mu_o\rangle$

Performance Predictions

Plasma duration

- Plasma duration is limited by:
  - OH volt-secs consumption
  - current drive parameter sustainment (power, density…)
  - thermal limits of limiters etc

- Available flux-swing $\Delta\phi$ is dictated by primary design
  - small tokamaks

    $$t_{pulse} = (\Delta\phi - 1.5\,IL)/\,V_{loop}$$

  - large tokamaks

    $$t_{pulse} = (\Delta\phi - 2 - IL)/\,V_{loop}$$

Performance Predictions

Confinement

- Tokamak discharges usually begin as OH, subsequently given P_{aux}.
  - OH confinement is given by scalings such as "TFTR":

$$\tau_E \approx 10^{-21}\, n a R^2 q_a^{0.5} \quad \text{(secs, m}^{-3}\text{, m, m)}$$

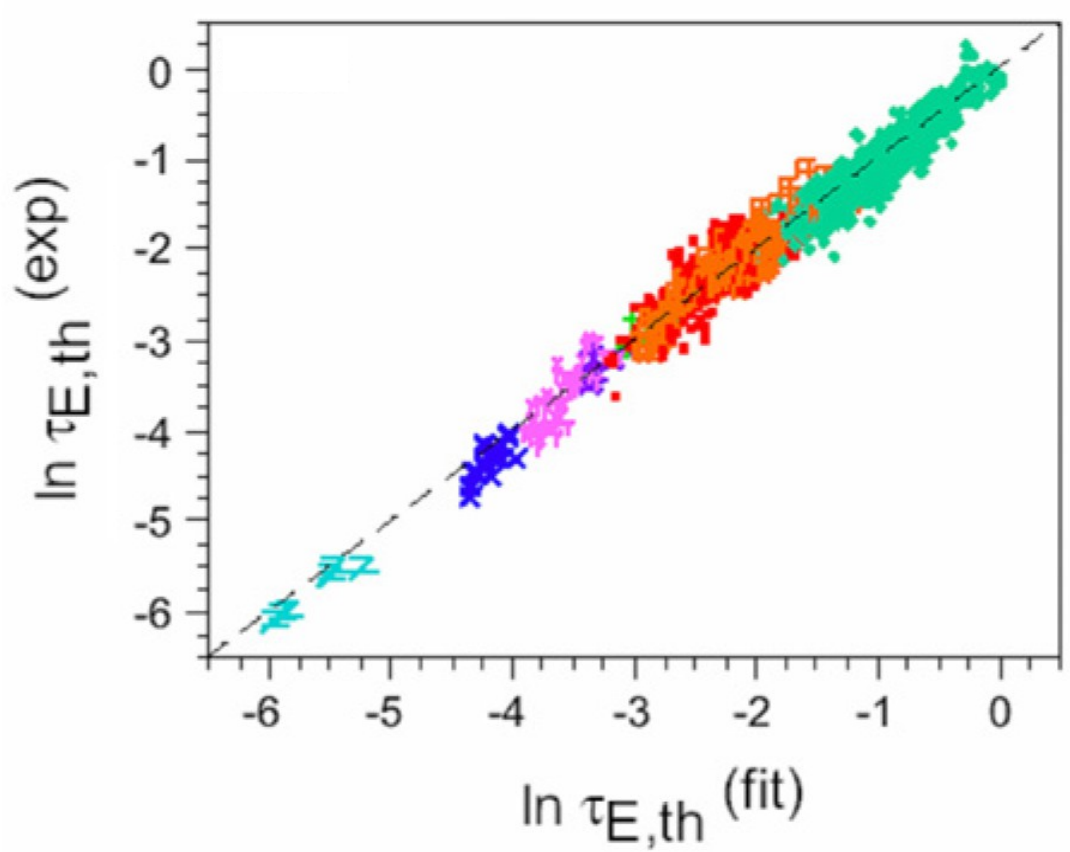
  - τ_p is generally about 4 xτ_E
  - Adding auxiliary heating always (?) degrades confinement
  - Slide-away discharges (OH or LHeH) can exhibit $\tau_E > \tau_{E\,OH}$
- See "How to Build a Tokamak" or Wesson for $\tau_E(P_{aux})$ scalings

Performance Predictions

Confinement

- ITER predictions drive strong interest in $\tau_E(P_{aux})$ scalings

$$\tau_{E,th} \sim I_p^{0.93} B_T^{0.15} n_e^{0.41} R^{1.97} \varepsilon^{0.58} \kappa^{0.78} M^{0.19} P_{L.th}^{-0.69}$$



Performance Predictions

Confinement analysis

- The usual equation for confinement time is:

$$\tau_E = W/(P_{tot} - dW/dt)$$

  - But what is W and what is P_{tot}?

- W (stored energy) should account for:
  - all particle species
  - non-Maxwellian distributions (tails)
  - anisotropic distributions

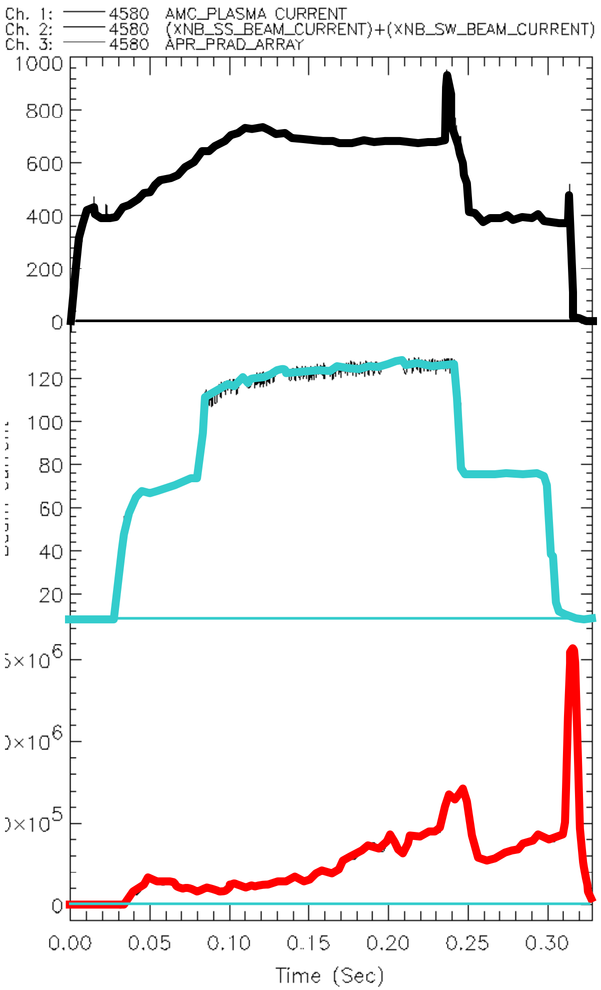
- P_{tot} (total absorbed power) should account for:
  - P_{rad} (impurities, ECE, bremstrahlung…)
  - P_{abs} (shine through, prompt losses)
  - P_{OH} (remembering all PF sources)
  - plasma-dissipated changes in inductive stored energy,

$$I_p^2(L_{int} + L_{ext})/2$$

Plasma Performance

Radiated power issues

(MAST)



Plasma current

Beam current

Bolometric power

Human Factors

Operations Planning

- Successful planning has to cover many elements
  - topical experiments
  - novel experiments
  - installation of new equipment
  - politics! (resource constraints, *raison d’être)*
  - maintenance
    - regular
    - remedial
- Try to keep a balance:
  - programmed focus
  - unplanned flexibility
- Use regular meetings to look ahead:
  - a few months (eg to suit conferences)
  - a week (eg to accommodate repair work)
  - a day (eg to accommodate unavailabilities)

Human Factors

Team building

- Only people ***truly in the team*** will enthuse!
  - experimental lead physicists
  - experimental support physicists
  - diagnosticians
  - technicians
  - (theoreticians?)

- These people must be present
  - in all planning meetings
  - in the control room
    - preferably in person
    - maybe by VR, including video links

Otherwise you will encounter considerable operational delays!

Human Factors

Safety

- Plant safety is covered by good design
  - known maxima of parameters
  - rigorous QA during manufacture and installation
  - engineered interlocks
  - sound commissioning tests
  - comprehensive operating procedures

- Human safety
  - Tokamaks feature a wide variety of safety hazards
  - Safety must have “buy-in” at all staff levels
    - area access interlocks
    - standing orders
    - personal protective equipment (gloves, hats)
    - management example and enforcement

Human Factors

Example tokamak safety issues

HAZARD	LOCATION	SAFETY MEASURE
Highly mechanically stressed metal components	Only in the load assembly itself	3m high solid concrete walled area around the load assembly
High currents (up to 100kA)	DC Buswork between supplies and load assembly	Buswork within HV areas or totally enclosed in earthed trunking
High Voltages (up to 20kV)	Capacitor bank areas	All within HV areas; earthsticks and multiple dumps and earths
Extreme high pressure hydraulic fluid - 300 bar	Load assembly and basement areas	Concrete walled HV areas, industry-standard components
X-ray radiation (strong function of operating parameters)	Originates where plasma electrons strike limiter components, affects areas adjacent to load assembly area	Concrete walled HV areas + lead blocks on control room side; real-time monitoring of X-ray fluxes and shot-shot alarms to guide operators
High pressure cooling water - 12.5 bar	Only in the coils in the load assembly	Generous margins in design and extensive testing of couplings,etc
Vacuum systems	Load assembly and basement areas	Pressure Vessel Approval procedures, industry standard components
High magnetic fields	~5 Tesla in the load assembly, ~1mT outside the HV areas	Large distance from the load assembly to HV area walls
Microwave heating	2MW at 60 GHz, 0.3MW at 1.3 GHz	PASS interlocked waveguide shutters, RF leakage survey, RF screening procedures

This work was funded by the UK DTI and by EURATOM.

Human Factors

Example tokamak safety issues

HAZARD	LOCATION	SAFETY MEASURE
200 degree Celsius hot objects	Load assembly (vacuum vessel) and ignitron heaters	HV areas inhibit personnel during bakeout
Suffocating gases	CO2 in microwave guide - potential leaks	Forced ventillation systems in MServices Area and controlled exhaust paths, interlocked gas supply
Inflammable gases	Deuterium and trimethyl borone puffed into vessel - potential leaks in the MServices Area	Hydrogen detectors; written handling procedures; fire alarms and controlled pumping exhaust paths with flame arrestors
Working at heights	Mezzanine floors in load assembly area, relative heights to basement	Hand rails, restricted access, hard hat mandates, regular testing of ladders
High pressure air (80 & 120 psi)	Vacuum valves,shutters, including air receivers	Industry-standard components, mandatory registration and testing
240 VAC mains	Everywhere - all three phases	Industry-standard components, mandatory testing
Loud noises	Originate in neighbouring Lightening Test facility	Warning signs and sound - insulated control room
Laser radiation	Diagnostic laser beams in the load assembly and basement areas	Operation interlocked to PASS, approved work procedures for maintenance,system inspections by LRO
Radioactive sources	Used for diagnostic calibrations	Screening cans, controlled stores, recorded holdings
Toxic materials	Small beryllium foils used in diagnostics, cleaning fluids	Controlled stores, inspections and discussions with COSHH Officer

This work was funded by the UK DTI and by EURATOM.

Summary

• **Successful tokamak operation requires a wide range of topics to be addressed:**

- thorough preparation of the machine
- at least a minimal set of plasma diagnostics
- consideration of gas breakdown and plasma current rise phenomena
- respecting the conventional operating limits (usually!)
- selecting diagnostics (etc.) that are consistent with predicted performance
- recognising how humans really work (and how they do not)

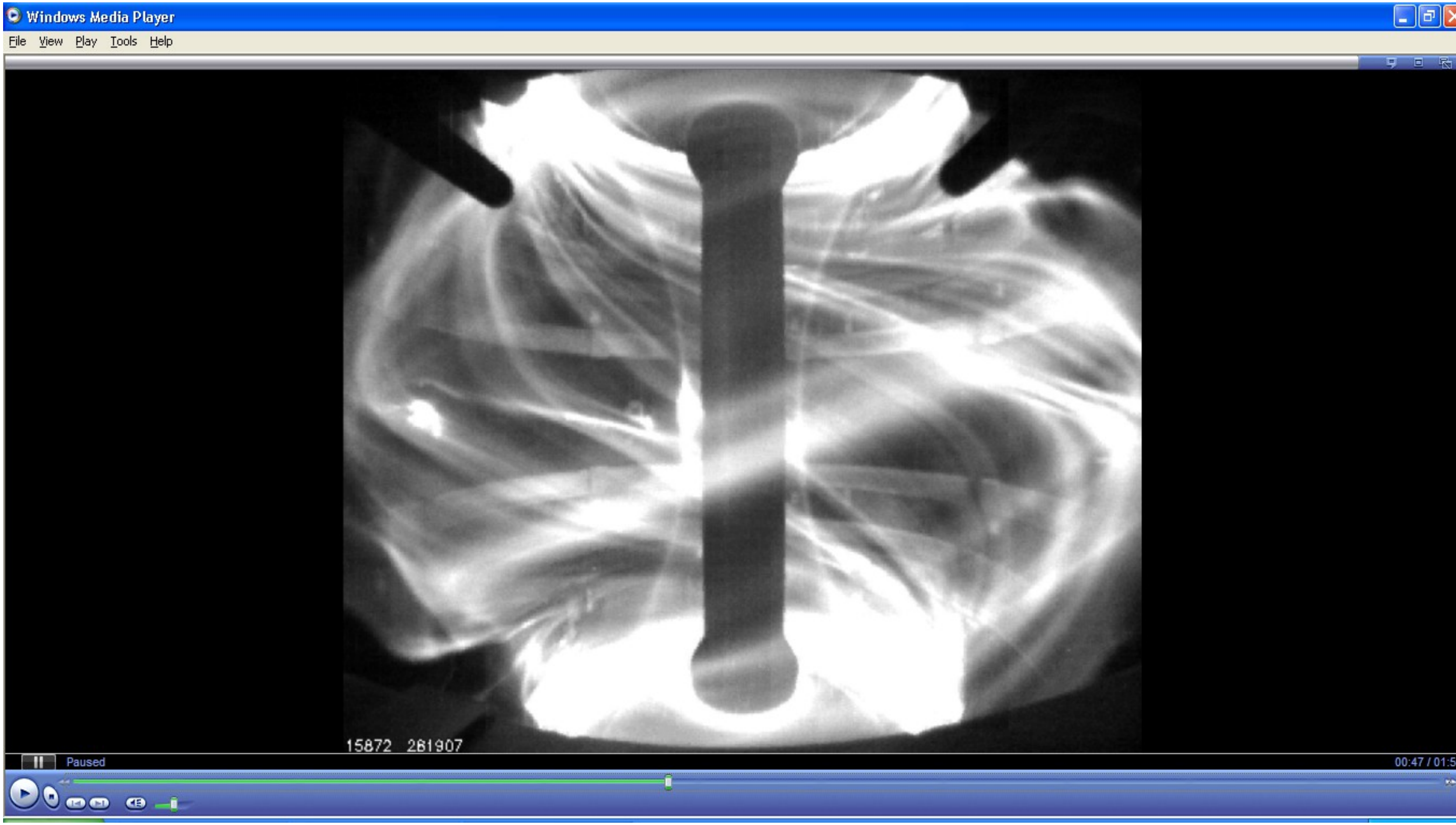
Get most of these right, most of the time,
and you will have a highly productive machine!

Successful Operation...

- **MAST plasma evolution (visible light, shot duration ~500ms)**

How to Operate a Tokamak

END



A giant Edge-Localised Mode in MAST

Machine Preparation

Electrical engineering

The contact resistance depends more on total pressure than on contact area. Fig.4 shows the relation between pressure and contact resistance for copper conductors[12]. Fig.5 shows the same for aluminium conductors[13]. For Fig.5 the surfaces were cleaned and pressed together with grease but this was not done for the Fig.4 curve and lower values could be obtained for copper conductors and the lower pressures.

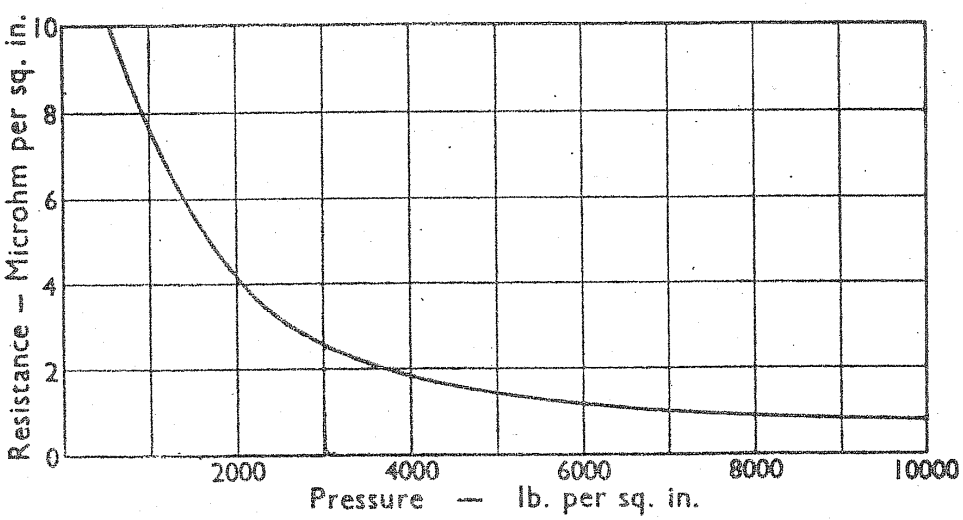
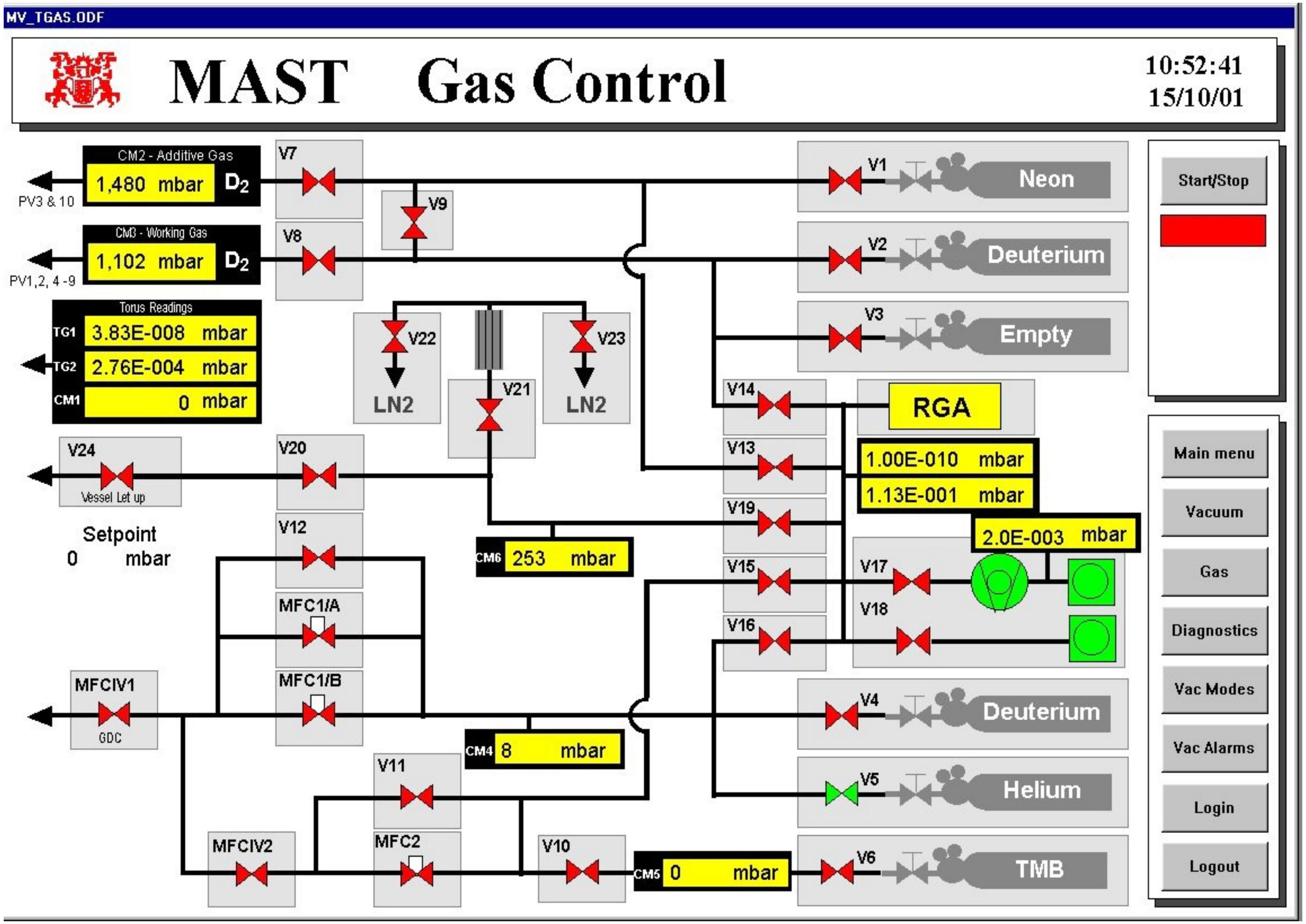


Fig.4. The effect of pressure on the contact resistance of a joint between two copper conductors. (To obtain the total joint resistance divide the ordinates by the contact area in sq. ins.)

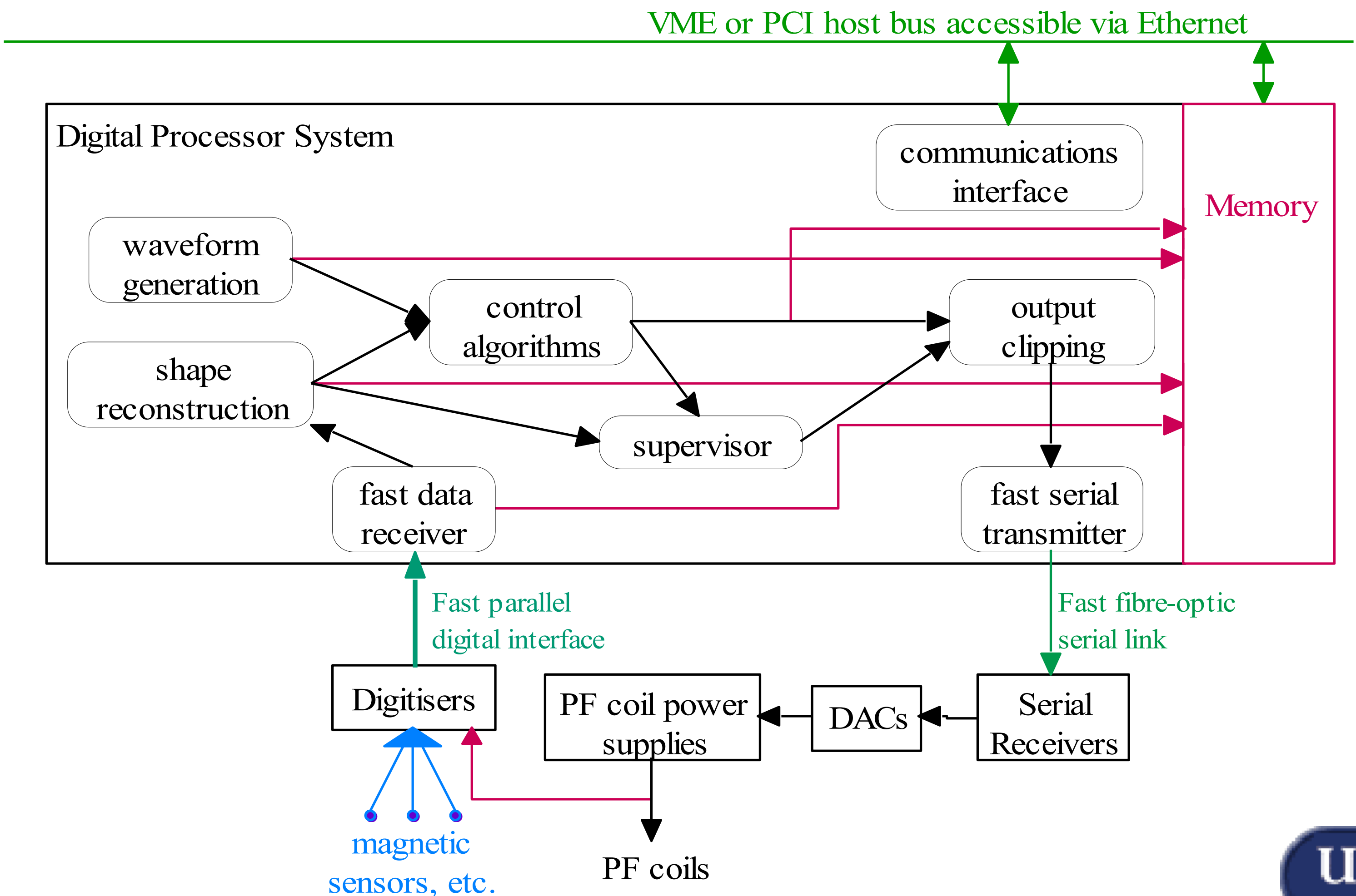
Machine Preparation

Vacuum and gas systems



Machine Preparation

Control system (MAST poloidal fields)

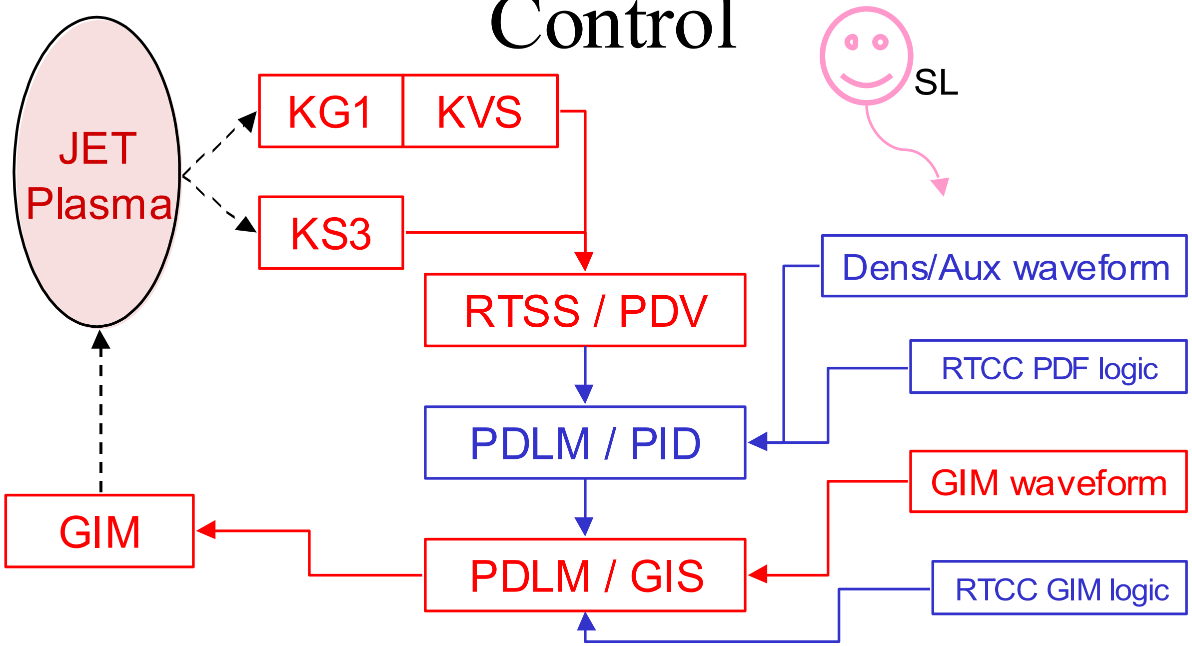


Machine Preparation

Control system (JET density feedback)

Plasma Density Validation and Control

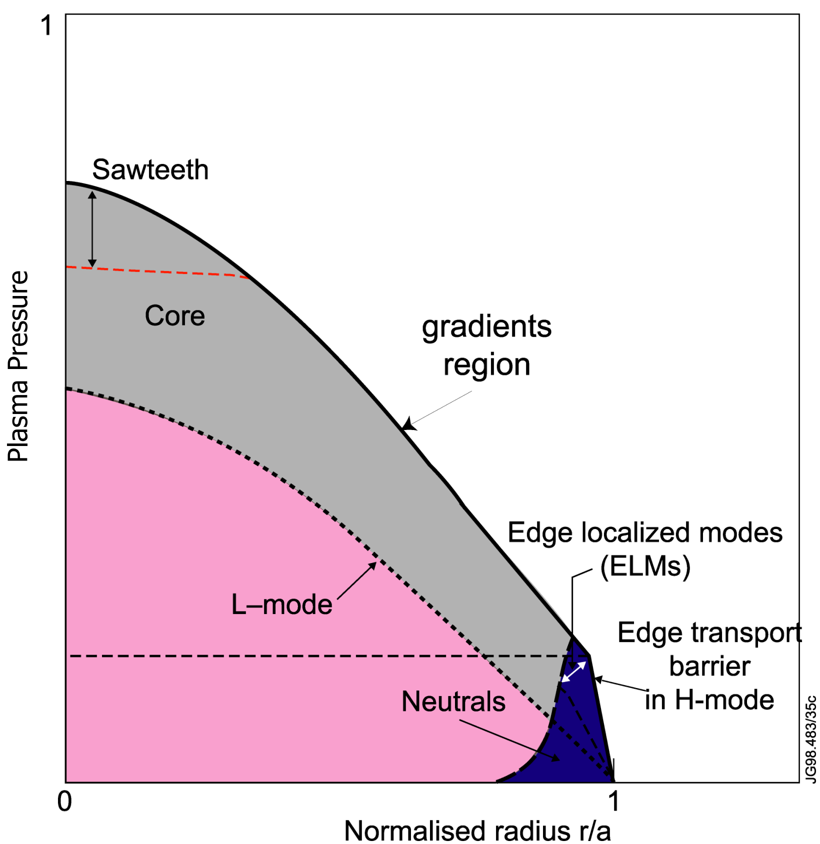
Function: control the plasma density.



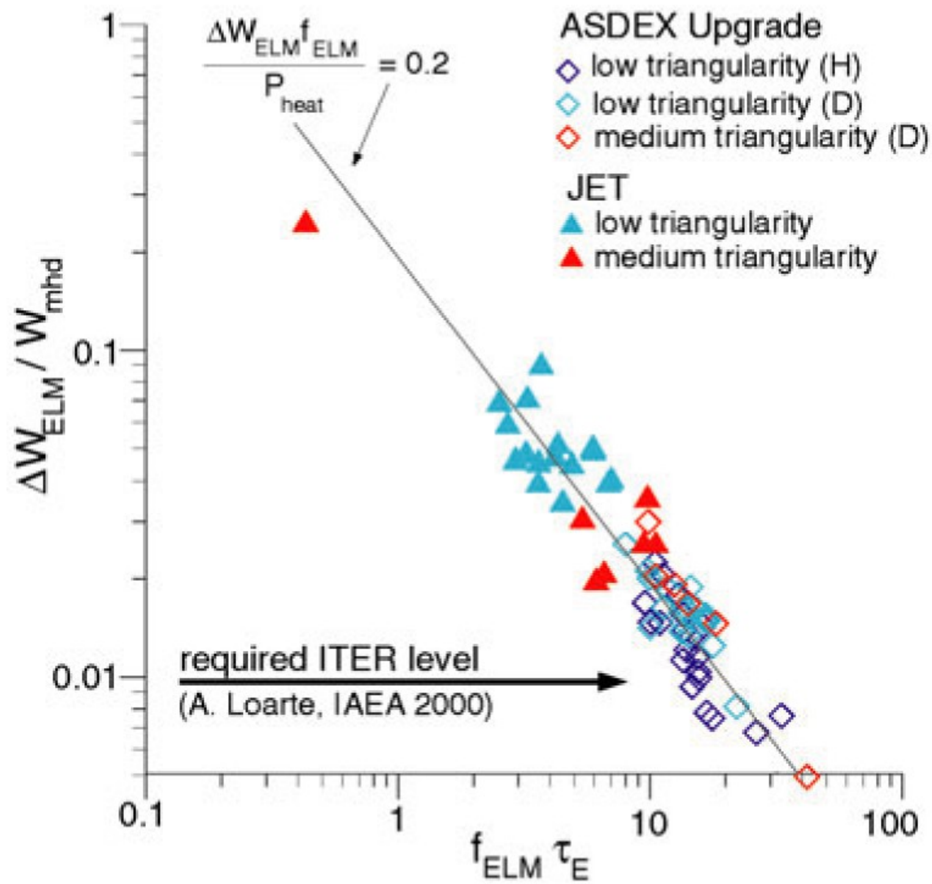
Plasma Operating Limits

Edge Localised Modes

Generic "H-Mode" plasma profile:



ELMs produce high energy pulses:



Performance Predictions

Current drive

- The power required to drive the toroidal plasma current scales in a similar way for lower hybrid waves and neutral beams:

  - LHCD

    $P_{LHCD} \approx IRn_{19}$ (MW, MA, m, m^{-3})

  - NBCD

    $P_{NBCD} \approx 5\ IRn_{19} / T_e \cos\phi_{beam}$ (MW, MA, m, m^{-3}, keV)

- NB there are also dependences on T_e (and Z_{eff}), details of antennae, beam geometry etc.

Human Factors

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    then
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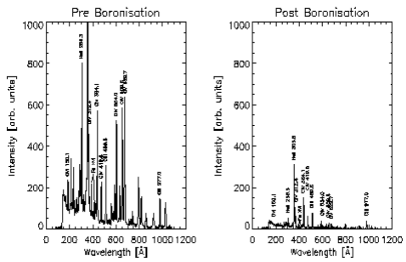

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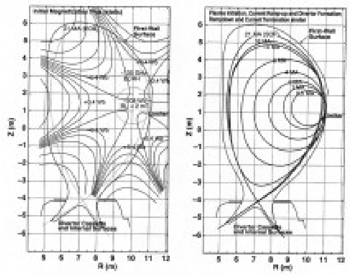

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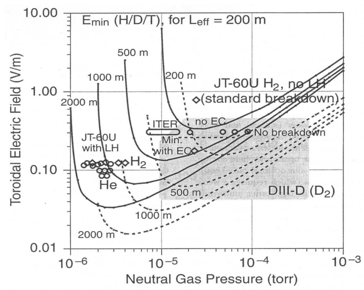

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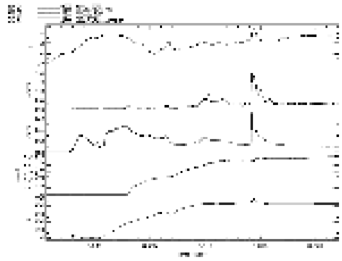

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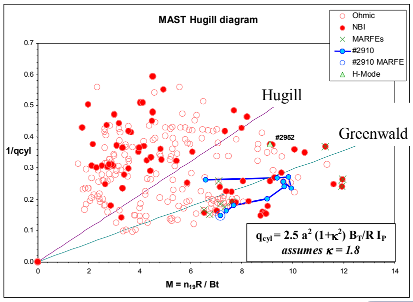
UKAEA Fusion

Plasma Operating Limits



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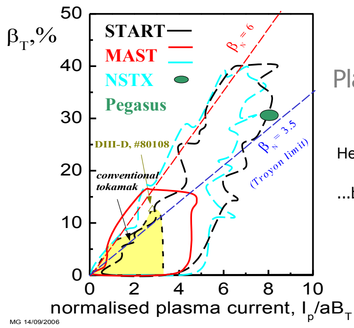
  - Both have resistive analogues with lower thresholds and non-linear saturation effects clamping achievable pressure

Plasma Operating Limits



Plasma pressure (MAST)

Here, $\beta_T = \langle p \rangle / (B_{\phi o}^2 / 2\mu_o)$

...but Troyon used:

$\langle p \rangle / \langle B^2 / 2\mu_o \rangle$

Performance Predictions

Plasma duration

- Plasma duration is limited by:
  - OH volt-secs consumption
  - current drive parameter sustainment (power, density…)
  - thermal limits of limiters etc
- Available flux-swing $\Delta\phi$ is dictated by primary design
  - small tokamaks
    $t_{pulse} = (\Delta\phi - 1.5\,IL)/ V_{loop}$
  - large tokamaks
    $t_{pulse} = (\Delta\phi - 2 - IL)/ V_{loop}$

Performance Predictions

Confinement

- Tokamak discharges usually begin as OH, subsequently given P_{aux}.
  - OH confinement is given by scalings such as "TFTR":

    $\tau_E \approx 10^{-21}\, naR^2 q_a^{0.5}$ (secs, m^{-3}, m, m)

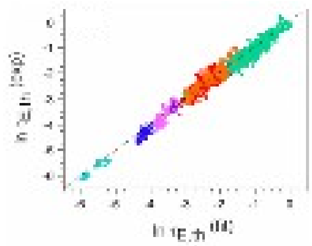
  - τ_p is generally about 4 xτ_E
  - Adding auxiliary heating always (?) degrades confinement
  - Slide-away discharges (OH or LHeH) can exhibit $\tau_E > \tau_{E\,OH}$
- See "How to Build a Tokamak" or Wesson for $\tau_E(P_{aux})$ scalings

Performance Predictions

Confinement

- ITER predictions drive strong interest in $\tau_E(P_{aux})$ scalings

$$\tau_{E,th} \sim I_p^{0.93} B_T^{0.15} n_e^{0.41} R^{1.97} \varepsilon^{0.58} \kappa^{0.78} M^{0.19} P_{L,th}^{-0.69}$$



Performance Predictions

Confinement analysis

- The usual equation for confinement time is:

  $\tau_E = W/(P_{tot} - dW/dt)$

  - But what is W and what is P_{tot}?

- W (stored energy) should account for:
  - all particle species
  - non-Maxwellian distributions (tails)
  - anisotropic distributions

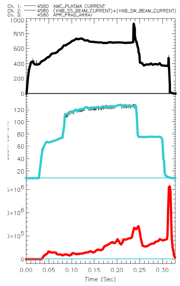
- P_{tot} (total absorbed power) should account for:
  - P_{rad} (impurities, ECE, bremstrahlung…)
  - P_{abs} (shine through, prompt losses)
  - P_{OH} (remembering all PF sources)
  - plasma-dissipated changes in inductive stored energy,

    $I_p^2(L_{int} + L_{ext})/2$

Plasma Performance

Radiated power issues

(MAST)



Human Factors

Operations Planning

- Successful planning has to cover many elements
  - topical experiments
  - novel experiments
  - installation of new equipment
  - politics! (resource constraints, *raison d'être)*
  - maintenance
    - regular
    - remedial
- Try to keep a balance:
  - programmed focus
  - unplanned flexibility
- Use regular meetings to look ahead:
  - a few months (eg to suit conferences)
  - a week (eg to accommodate repair work)
  - a day (eg to accommodate unavailabilities)

Human Factors

Team building

- Only people ***truly in the team*** will enthuse!
  - experimental lead physicists
  - experimental support physicists
  - diagnosticians
  - technicians
  - (theoreticians?)

- These people must be present
  - in all planning meetings
  - in the control room
    - preferably in person
    - maybe by VR, including video links

Otherwise you will encounter considerable operational delays!

Human Factors

Safety

- Plant safety is covered by good design
  - known maxima of parameters
  - rigorous QA during manufacture and installation
  - engineered interlocks
  - sound commissioning tests
  - comprehensive operating procedures

- Human safety
  - Tokamaks feature a wide variety of safety hazards
  - Safety must have "buy-in" at all staff levels
    - area access interlocks
    - standing orders
    - personal protective equipment (gloves, hats)
    - management example and enforcement

Human Factors

Example tokamak safety issues

HAZARD	LOCATION	SAFETY MEASURE
Highly mechanically stressed metal components	Only in the load assembly itself	3m high solid concrete walled area around the load assembly
High currents (up to 100kA)	DC Buswork between supplies and load assembly	Buswork within HV areas or totally enclosed in earthed trunking
High Voltages (up to 20kV)	Capacitor bank areas	All within HV areas; earthsticks and multiple dumps and earths
Extreme high pressure hydraulic fluid - 300 bar	Load assembly and basement areas	Concrete walled HV areas, industry-standard components
X-ray radiation (strong function of operating parameters)	Originates where plasma electrons strike limiter components, affects areas adjacent to load assembly area	Concrete walled HV areas + lead blocks on control room side; real-time monitoring of X-ray fluxes and shot-shot alarms to guide operators
High pressure cooling water - 12.5 bar	Only in the coils in the load assembly	Generous margins in design and extensive testing of couplings,etc
Vacuum systems	Load assembly and basement areas	Pressure Vessel Approval procedures, industry standard components
High magnetic fields	~5 Tesla in the load assembly, ~1mT outside the HV areas	Large distance from the load assembly to HV area walls
Microwave heating	2MW at 60 GHz, 0.3MW at 1.3 GHz	PASS interlocked waveguide shutters, RF leakage survey, RF screening procedures

This work was funded by the UK DTI and by EURATOM.

UKAEA Fusion

Human Factors

Example tokamak safety issues

HAZARD	LOCATION	SAFETY MEASURE
200 degree Celsius hot objects	Load assembly (vacuum vessel) and ignitron heaters	HV areas inhibit personnel during bakeout
Suffocating gases	CO_2 in microwave guide - potential leaks	Forced ventillation systems in MServices Area and controlled exhaust paths, interlocked gas supply
Inflammable gases	Deuterium and trimethyl borone puffed into vessel - potential leaks in the MServices Area	Hydrogen detectors; written handling procedures; fire alarms and controlled pumping exhaust paths with flame arrestors
Working at heights	Mezzanine floors in load assembly area, relative heights to basement	Hand rails, restricted access, hard hat mandates, regular testing of ladders
High pressure air (80 & 120 psi)	Vacuum valves,shutters, including air receivers	Industry-standard components, mandatory registration and testing
240 VAC mains	Everywhere - all three phases	Industry-standard components, mandatory testing
Loud noises	Originate in neighbouring Lightening Test facility	Warning signs and sound - insulated control room
Laser radiation	Diagnostic laser beams in the load assembly and basement areas	Operation interlocked to PASS, approved work procedures for maintenance,system inspections by LRO
Radioactive sources	Used for diagnostic calibrations	Screening cans, controlled stores, recorded holdings
Toxic materials	Small beryllium foils used in diagnostics, cleaning fluids	Controlled stores, inspections and discussions with COSHH Officer

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Summary

- **Successful tokamak operation requires a wide range of topics to be addressed:**
  - thorough preparation of the machine
  - at least a minimal set of plasma diagnostics
  - consideration of gas breakdown and plasma current rise phenomena
  - respecting the conventional operating limits (usually!)
  - selecting diagnostics (etc.) that are consistent with predicted performance
  - recognising how humans really work (and how they do not)

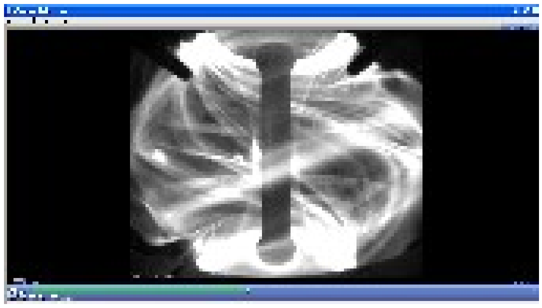
Get most of these right, most of the time,
and you will have a highly productive machine!

Successful Operation...

- **MAST plasma evolution (visible light, shot duration ~500ms)**

How to Operate a Tokamak

END



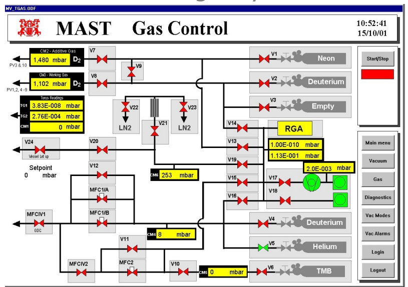
A giant Edge-Localised Mode in MAST

Machine Preparation

Electrical engineering

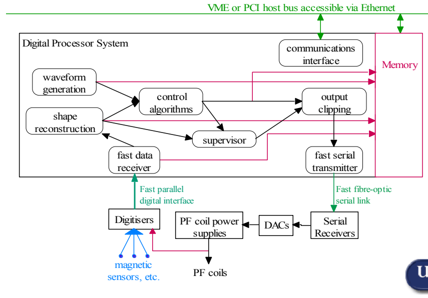
Machine Preparation

Vacuum and gas systems



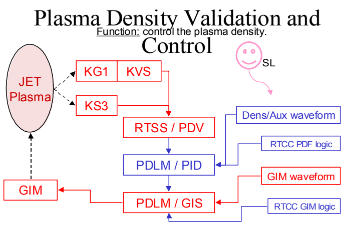
Machine Preparation

Control system (MAST poloidal fields)



Machine Preparation

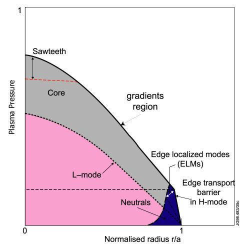
Control system (JET density feedback)



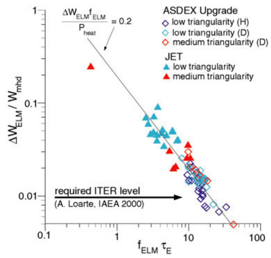
Plasma Operating Limits

Edge Localised Modes

Generic "H-Mode" plasma profile:



ELMs produce high energy pulses:



Performance Predictions

Current drive

• The power required to drive the toroidal plasma current scales in a similar way for lower hybrid waves and neutral beams:

- LHCD
  $P_{\mathbf{LHCD}} \approx I R n_{\mathbf{19}}$ (MW, MA, m, m^{-3})

- NBCD
  $P_{\mathbf{NBCD}} \approx 5\, I R n_{\mathbf{19}} / T_e \cos\phi_{\mathbf{beam}}$ (MW, MA, m, m^{-3}, keV)

• NB there are also dependences on $T_{\mathbf{e}}$ (and Z_{eff}), details of antennae, beam geometry etc.

Human Factors

Team building