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Diagnostics for Machine Protection of DEMO

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Abstract. DEMO aims to (i) integrate, demonstrate and validate all relevant technology necessary to convert fusion energy to electrical energy and (ii) that the machine and its operations are economically and environmentally acceptable. To maintain the efficiency and availability of the machine, there are several physics and combined physics/technology issues as well as the engineering issues. Machine Protection (also known as Protection of Investment) addresses both the risks to plant (to avoid costly repair or replacement) and the risks to normal operating time (to avoid loss of productivity and the return on investment). The plasma-related Machine Protection issues involve measurement and control of plasma stability, plasma purity, and plasma-wall interactions. Machine Protection aims to avoid hitting catastrophic limits by using early warning alarm systems, and controlled termination or avoidance, involving coordinated actions of the magnets, gas and auxiliary heating or current-drive systems. This article outlines the key processes, some of which are used in present-day tokamaks and some of which are new specifically for DEMO (e.g. First wall and divertor power handling) and reveals the need to research and develop new science and technology for Machine Protections in DEMO's high radiation and thermal fields.This work was funded by the RCUK Energy Programme under grant EP/I501045 and the European Communities under the contract of Association between EURATOM and CCFE and conducted partly under EFDA PPPT (WP13-DAS04). The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Keywords: fusion, DEMO, diagnostics.
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1. INTRODUCTION

The first power-generating fusion plasma machine, DEMO, must integrate, demonstrate and validate all relevant technology *[ref 1]*, in particular (i) structural materials, functional materials manufactured components and assemblies tolerant of high radiation and heat loads, (ii) plasma facing materials having low erosion and sputtering, (iii) magnets, gas-handling, additional heating systems and plasma diagnostic systems operating in high radiation fields, high magnetic fields, tolerant of thermal and mechanical cycling, (iv) (radio)-active gas handling, accounting and Tritium self-sufficiency, (v) energy conversion, i.e. power to the grid and (vi) not least, approval by Nuclear Agency.

DEMO must show Fusion is economically and environmentally acceptable *[ref 1]*. The economic issues involve Availability, Reliability, Maintainability, Plasma Performance, Energy conversion efficiency, and Whole-life Cost / Benefit. The environmental issues involve efficient use of Materials (including Helium, a scarce resource), Passive Safety and Low-level active waste.

Many workers have studied and continue to study specific areas of the science and technology of DEMO *[ref 2 to 8 and references therein]*. This article merely attempts to give an introductory overview of the Machine Protection issues related to fusion plasma.

Machine Protection (also known as Protection of Investment) addresses both the risks to plant (to avoid costly repair or replacement) and the risks to normal operating time (to avoid loss of productivity and the return on investment). It complements the Machine Safety programme which focusses on risks to humans, be the risk of a localised hazard or wider-area hazard.

Much of the Machine Protection programme is concerned with operation of vacuum, radio-active material handling, heat transfer, power conversion, site services, etc., to ensure that the plant runs efficiently and does not blow up, burn out, damage environment, etc.. The risks and mitigations are mainly engineering issues and are not discussed further here.

A measure of DEMO success is the "Cost of Electricity", *CoE [ref 1]*
$CoE \propto 1 / (A0.6\ \ \eta th0.5\ \ Pe0.4\ \beta n0.4\ NGW0.3)$

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where *A* is Availability, *ηth* is Thermodynamic efficiency, *Pe* is Electrical power, *βn* Plasma pressure/magnetic pressure and *NGW* the Greenwald density limit. These factors are not independent. For example, there is little value in having the capability of high *βn* if the necessary additional heating is not available for much of the time. Furthermore, both the scientific and technological features have to be incorporated in an holistic design so that where there are underlying dependencies the scientific and technological thinking can converge on a solution satisfying all points of view. For example, the divertor heat load physics problem could be solved by increasing the size of the machine, but this would increase the nuclear island with consequent impacts on design, build, operations and de-commissioning.

Generally, DEMO's measurement and control systems will have to cope with transient and permanent radiation induced damage, as well as thermal and mechanical cycling *[ref 9,10,11 and references therein]*. Existing designs will not, in general, work. For example, present-day machines rely on magnetic pick-ups to control breakdown, current rise and shaping, flat top and termination. In DEMO, the levels of radiation would exclude any electronic devices, such as magnetic pick-ups, being located close to the plasma.

Section 2 outlines the conditions in DEMO relevant to sensors and actuators used in Machine Protection for plasma operations.

Section 3 addresses the basic plasma diagnostics for Machine Protections, covering (i) plasma stability :- position, high β, high density, MHD, etc., (ii) plasma purity :- radiative impurity gas, He ash, W accumulation, etc., and (iii) plasma-wall interactions :- protection of plasma-facing components e.g. tiles, auxiliary heating launchers, etc.

Section 4 addresses management of Machine Protection :- design and build qualification, operating qualification.

Section 5 concludes the article.

2: DEMO CONDITIONS

Most of the Fusion-Power-Plant simulations work with a target electrical output of ~ 500 MW, which implies a fusion power of ~ 1500 MW, allowing for the power conversion efficiency . Of the total fusion power, 1200 MW is carried by the neutrons, and 300MW is carried by the alpha particles. The neutron power is absorbed in the neutron blanket (!) and the heat transferred to the electricity generators. The alpha power heats the plasma, and reaches equilibrium with power lost by particle flux to the wall, particularly the divertor, and also Bremsstrahlung, and synchrotron radiation. The particle flux power is much larger the Bremsstrahlung and synchrotron powers and would destroy the divertor in a very short time. So, most simulations assume that the particle flux power is radiated over the entire 1st wall by the injection of some high-Z impurity, such as Neon or Argon. For the expected power-handling capability of the divertor ~ 5 MW.m^{-2}, the radiated power fraction must be ~ 90 % !!!. Such a high radiated fraction can be achieved in today's machines only in specially designed experiments, but in DEMO, this must be the normal operating condition.

The high energy neutron field and associated ionising radiation also constrains the measurement and control systems close to the plasma. The sensors, actuators and associated wiring would be heated by the neutrons. Radiation-induced conductivity would degrade the insulators, and also radiation-induced and temperature-induced EMFs would be generated. These would have transient effects, leading to very poor signal/noise, and permanent effects, leading to total loss of function. Probably, the only remedy is to position the sensors and actuators beyond the neutron blanket.

3: PLASMA DIAGNOSTICS FOR MACHINE PROTECTION

DEMO must ensure the stability and purity of the plasma. If the purity were compromised, the fusion yield will be reduced, and a disruption might follow. If a high current, high energy plasma were to disrupt the machine structure would be damaged, resulting in at least a loss of operational time, and, more seriously, there may be a release of radio-active gasses exceeding the permitted levels. Many workers have studied the diagnostics required to measure and control the plasma *[ref 9,10,11 and references therein]*, here we consider the general Machine Protection issues – function, and availability.

3.1 : Magnetics

DEMO must ensure that plasma is where it should be in relation to the plasma-facing components. That is, the DEMO control system must control the position and shape of the last-closed-flux-surface (LCFS), i.e. the plasma centre, the X-point, the strike points, the flux expansion of the X-point legs, and distances between the LCFS and key points on the vessel interior. It must also control the plasma current which depends on the resistivity of the plasma, which, in turn, depends on gas, impurity accumulation, additional heating and MHD structure.

In present-day machines, the control systems rely on magnetic pick-ups located close to the plasma. In DEMO, the pick-ups would be located beyond the neutron absorbing blanket. The blanket's functional and structural materials would screen to some extent the magnetic fields, so the control must be designed and operated mindful of a systemic time delay. The control has to steer the programmed evolution of the plasma from breakdown, through current rise and shaping, flat-top and termination. On the way, there are risks to stability such as MHD activity and changes in shape and plasma pressure due to heating as well as risk to plasma-facing components due to excessive particle flux. The hazards and risks are different in the different phases of the plasma. The control has to monitor these and, when the risk is significant, switch to a different programme designed to reduce the risk and/or minimise the potential damage. The screening effect of the blanket imposes a time constraint on the protection – the protection can not act faster than the screening time-constant, so the alarm levels may have to be set quite low to give time for the control to switch to the recovery programme. The same screening applies to the dynamics of the poloidal field magnets. In present machines, the response is usually to terminate the plasma. In DEMO, the need for high return on investment may require the control takes risk-avoidance action but then returns to the intended programme, as near as possible. Clearly, there is some compromise of sensitivity-to-risk and availability-of-performance to be determined.

The control system needs measurements of magnetic field and flux. In present machines, these are achieved with simple pick-up coils, whose output is proportional to the rate-of-change of flux, and an electronic integrator. In DEMO's long pulses (hours) the conventional integrator would drift too much, so a new approach has to be found.

In present-day machines the pick-ups and associated wiring are not 100% reliable. They were not designed to be replaced and so faulty pick-ups are left in place, and their function is provided by similar pick-ups in other toroidal locations. In DEMO, the pick-ups and wiring must have a higher electrical and mechanical integrity and good resilience to radiation induced effects as, even though they will be behind the neutron blanket, there will still be significant radiation levels. Clearly, DEMO will have to have to toroidally duplicated pick-ups, and, given DEMO's 30 year lifetime, there should be some mechanism to replace them in order to maintain adequate coverage.

3.2 : Gas and Density

As described above, Machine Protection for DEMO involves both protection of equipment and maximising availability. To achieve its high performance goals, the control system has to establish and maintain (i) a high plasma density, around the Greenwald limit, and (ii) a highly radiating plasma, with a radiating fraction ~90%. At the same time, it has to cope with (i) the sudden application or removal of additional heating, (ii) the generation of alpha particles from the fusion reaction, and (iii) disturbances due to core and edge MHD phenomena. The key measurement is the plasma density. In present-day machines, this is usually measured by interferometry, and/or polarimetry which yield a line-integrated density or Thomson scattering and/or LIDAR which yield a density profiled across the plasma cross-section. Interferometry attempts to track phase changes, but if the instrument is not fast enough and there is a sudden phase change (due to e.g. a large Edge Localised Mode, ELM) the reported value may be incorrect (known as a fringe jump). Polarimetry provides an instantaneous value and does not suffer from the fringe jump problem, but does require knowledge of the magnetic field along the line of sight, particularly the components perpendicular to the line. They all require high reliability, high power lasers, optics and detectors. In DEMO, these components would be located beyond the neutron absorbing blanket and probably beyond the primary containment shield which put mechanical stability constraints on the optical path and components. The requirements for Tritium self-sufficiency (quantified by the Tritium breeding ratio, TBR) and for high availability constrains the number and size of optical ports in the blanket but the constraints are in opposition. For high TBR, the view-ports should be as few and as small as possible while for high availability, the view ports should be as many and as large as possible. A comprise has to be determined, probably allowing for sets of vertical and horizontal lines of sight at different toroidal locations.

In many tokamaks, gas is introduced through electronically controllable valves, often using piezo-electric valves. DEMO could use similar, but they would have to be well shielded and located beyond the neutron shield. Such arrangement will introduce time delays which will compromise the density feedback control.

Machine Protection issues relating to the vacuum vessel involve the integrity and the availability of the vessel. The vacuum conditions must be monitored continuously to check for leaks and to check the residual gas is suitable for plasma operations. Both of these are challenging in DEMO because of the high radiation and magnetic fields. The pressure ranges from “air (before evacuation)” ~ 1 bar to ultra-high-vacuum (UHV) ~ 1e-7 bar. Conventional UHV pressure gauges are based on measurement of currents in ionized gas – in DEMO there will be significant residual ionized gas. Conventional Residual Gas Analysis (RGA) uses electro-magnetically tuned massspectrometers close to the plasma vessel. So, both the gauges and the RGA would need to be extremely well shielded in DEMO and located beyond the neutron absorbing blanket. The consequent time delays will compromise analysis.

3.3 Plasma Stability

There are many forms of instability in hot plasmas – oscillations in the core of the plasma (sawteeth), oscillations in the edge of the plasma (Edge Localised Modes, ELMs), magnetic islands, impurity accumulation in the core and in influxes in the edge (MARFEs), runaway electrons. Some of these may grow and cause the plasma to terminate abruptly (disruption). DEMO will be designed to tolerate a few disruptions at full current and energy, but the risks to the integrity of the vessel, the plasma-facing components and even the external components must be appreciated.

The first issue is how to avoid getting into an critically unstable condition by design. Plasma modelling should develop over the next few years to identify many risky magnetic and kinetic conditions and, then, how to quell the disturbance and return to safe operation, albeit at the expense of performance. It may be possible to design plasma shapes, current, gas and heat which avoid avoiding over-heating localised contact points and so reduce the risk of triggering release of impurities from the divertor and first wall.

The second issue is how to detect critically unstable conditions in real-time. Already there are experimental diagnostics to identify core and edge modes, magnetic islands, etc. and some have been used to switch magnetic and kinetic control modes and achieve a soft landing – these would need to be developed into real-time, high integrity systems for DEMO.

Third, is to design and execute an appropriate response. Some conditions may be recoverable and after switching to a recovery mode, the intended programme can be resumed. Some conditions may be terminal – the response would involve the magnet, gas and heat controllers to reduce the energy to zero in the plasma in a controlled manner, as quickly as possible. Some conditions may be so unstable that there is no time for any of the control actuators (magnets, gas, heat) to act – then the only option is to inject massive amounts gas to dissipate the plasma energy. During such catastrophic events, there still needs to be high integrity measurements of the vacuum (pressure, gas mix) the vessel (displacements, forces, induced currents), the neutron blanket, the magnets, etc.. These last few sensors will be a challenge in DEMO, operating in high ionising radiation fields but also requiring immunity to high levels of electro-magnetic interference (EMI).

3.4 Plasma / Heating System Interactions

In DEMO, the plasma will be heated with neutral beams and radio-frequency and/or microwave beams.

Most of the neutral beam energy will be absorbed in the plasma but some will pass through the plasma and land on tiles in the beam path. The "shine-through" protection estimates the energy deposited on tiles in the neutral beam path using the plasma density and beam energy. If this deposited energy is too high, the tiles would be at risk of melting or worse so the protection logic would switch the beams off.

At the radio frequency and microwave antennae, there is a risk that the high voltage may cause local arcing if there is too much ionised gas in the vicinity. This arcing may damage the antenna and also may lead to impurities in the plasma and a disruption. In existing machines, this arcing can be observed by cameras, and the plasma steered to terminate. In DEMO, conventional cameras located in wide-angle viewports will not work because of the high radiation, and novel cameras and optics will have to be developed. Alternatively, a local measurement of Bremsstrahlung (which depends on density) could monitor the gas in the vicinity of the antenna.

3.5 : Fusion plasmas

From the viewpoint of long-term availability, the most at-risk components are the plasma facing components. There must be periodic inspections to check their electro-mechanical integrity. This requires robotic, non-invasive techniques e.g. cameras for visual inspection, acoustic probes to check for loose mountings and internal defects, material samplers, local cleaners, and, not least, irradiation meters. Present-day machines use visible and IR cameras and thermocouples, but suffer from in-sufficient coverage and the cameras rely on knowing the emissivity of the objects in view, which is not always stable. In DEMO, thermocouples embedded in tiles would be useful only in the first operations before burning plasma, thereafter, the signals would be so degraded and the sensors themselves would be un-maintainable. It may be possible to use cameras with appropriate optics, but their fields of view would be very limited. As a minimum protection, two-colour spot pyrometers should be trained on critical areas, but even these would have to view through mirrors-in-labyrinths, and the mirrors themselves may confuse the readings.

As mentioned above, one key operating condition is with a high radiated power fraction. In present-day machines, the radiated power is measured with bolometer cameras having ~ 50 lines of sight, directly viewing the plasma. In DEMO, the lines of sight would have to be provided by mirrors-in-labyrinths to avoid direct exposure to the neutron flux, and these would complicate the interpretation of the signals. It may be possible to estimate the radiated power indirectly, using the neutron blanket coolant temperature which would depend on the neutron power and the radiated power.

Over its lifetime, DEMO will develop burning plasmas using reaction rate sensors and fuelling and heating actuators to control the burn. From the outset, the Machine Protection interest would be to identify potential run-away or ignition conditions and then to have an automatic change in the programmed sequence to avoid the un-controlled ignition.

4: MANAGEMENT OF MACHINE PROTECTION

In fission reactors there are Design Qualification policies and procedures covering the structural and functional materials, fabrication of components, assembly and integration into the machine systems, including Control and Instrumentation (C&I) *[ref 12,13]*. In DEMO, there will be similar Design Qualifications covering the integrity of in-vessel components, the 1st wall, neutron blankets, heat transfer, and the overall containment etc., but there will also be new qualifications to give assurance of the function and availability of much more complex systems such as the measurement and control of the plasma's magnetic structure, the plasma's composition and density, and, not least, the the fusion burn. These issues would be best addressed in a model-based system engineering approach *[ref 14,15,16]* addressing function, availability, Machine Protection and Safety for the view-points of the various interested parties (e.g. owner, designer, constructor, operator, regulator) but as yet, there is no framework for a consistent and coherent set of such qualifications. The scientists and engineers must develop such a framework and undertake training in its use.

DEMO's operational limits will develop from independent commissioning of separate systems, to checks of basic measurement control (magnetics, density) to checks with heating systems and ultimately to fusion burn. At each stage, an assurance body will establish the operating limits, consistent with the function and availability of the plant at the time. The operating procedures will be implemented in configurable programmes in the control computer systems. At each phase of the plasma (beak-down, current rise and shaping, flat-top, heat, burn, cool, terminate), a programme has to steer the plasma through the main sequence, coordinating magnets, gas, and heating. Additionally, it has to monitor critical personnel Safety and Machine Protection conditions and, if necessary, switch to a Machine Protection or Safety sequence. Each of these plasma phases (with their conditions and transitions) will need qualification and re-qualification as the operational envelope develops over the years.

5: SUMMARY AND CONCLUSIONS

This article has attempted to outline some of the Machine Protection issues concerned with burning plasma in DEMO. Many of the techniques used on present-day tokamaks will not be not usable on DEMO because of the high radiation and high thermal fields, but there are avenues of Research and Development which should be pursued to help bring about control of the fusion power plant. Specifically :-

- Periodic detection of risky conditions in in-vessel components:- electro-mechanical integrity, erosion, deposition, irradiation using remote-controled cameras, acoustic probes,material samplers, local cleaners (e.g. laser), radiation meters, etc..
- High integrity, real-time vessel condition monitors capable of operation during a disruption, e.g. vessel displacement, forces, currents, pressure, gas-mix – the last two, not using ionised gas techniques
- Tritium compatible, high integrity gas introduction valves capable of withstanding many cycles of operation in high radiation and thermal fields (i.e. probably not piezo).
- High integrity, replaceable magnetic field sensors and wiring, and stable signal integrators.
- In-situ calibration of magnetics, interferometer/polarimeters, spectrometers, thermal and neutronic diagnostics.
- Real-time detection of risky conditions in in-vessel components :- hot-spots, arcing
- Real-time detection of risky conditions in the core, edge and divertor plasmas :- magnetic modes and islands, density peaking, pressure peaking, impurity accumulation, near-ignition, detachment, He- ash levels
- Magnetic control with time delays due to shielding, at several toroidal and poloidal locations for redundancy.

- Density control with time delays due to gas introduction located at some distance from the plasma at several toroidal and poloidal locations for redundancy.
- High radiation fraction control :- Measurement of radiated power. Control of radiating impurity gas injection with transport delays
- Burn control :- Control of fuel mix with time delays. Avoidance of run-away conditions
- Design qualification, and a framework for structured, coherent and consistent model-based design covering function, availability, safety and machine protection
- Qualification and re-qualification of operational scenarios – modelling and experimental validation of plasma configurations, assessment of risky conditions and acceptable transitions. There is a catch-22 :- to have valid plasma measurements and controls, you need to have good plasmas, but to have have good plasmas you need good measurements and controls.

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