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Engineering Challenges for ITER Diagnostic Systems

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Engineering Challenges for ITER Diagnostic Systems

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There will be 50 diagnostic systems installed on ITER. All have been implemented with great success on experimental fusion reactors around the world. Despite this deep experience, implementation of diagnostic systems on ITER remains very challenging. Structural, nuclear and optical engineering challenges arise from loads that are at least an order of magnitude higher and last for much longer than any previous experiment. Complicating this challenge is an acceleration of the design process because the systems delivered to ITER must be ready for full power D-T operations from day-One. Talented engineering teams around the world are tackling these challenges in many innovative ways. In this paper ITER diagnostic systems from the US will be used to show a selection of examples of how the "D-T Ready" engineering challenges are being answered.

Keywords: ITER Diagnostic Engineering, High Temperature Plasma Diagnostics

I. INTRODUCTION

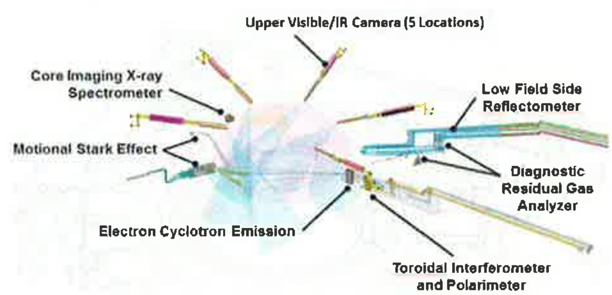
There will be 50 diagnostic systems installed on ITER. All have been implemented with great success on experimental fusion reactors around the world. Despite this deep experience, implementation of diagnostic systems on ITER remains very challenging. Difficulties arising from the steady-state reactor-like conditions are multiplied by a highly constrained integration package and myriad safety and quality requirements.

In this paper a sample of solutions to diagnostic mechanical and optical engineering challenges will be provided based on the seven USDA ITER diagnostic systems. Teams of engineers and physicists around the world are tackling similar issues for the other partner DAs and ITER. While the USDA portfolio is not exhaustive it provides a broad sample of how diagnostic engineering challenges are being met. Table 1 provides a summary of the US ITER diagnostic systems and acronyms used in this paper.

TABLE I. US ITER DIANGOSTIC SYSTEMS

Diagnostic System	*Primary Measurement*	*Acronym*
Diagnostic Residual Gas Analyzer	*Concentrations of neutral gases in the plasma*	*DRGA*
Low Field Side Reflectometer	*Aspects of Plasma Density*	*LFSR*
Electron Cyclotron Emission	*Plasma Electron Temperature Profile*	*ECE*
Toroidal Interferometer and Polarimeter	*Apects of Plasma Density*	*TIP*
Upper Port Wide Angle View Visible and Infrared Cameras	*Vis and IR Views of divertor and blanket wall*	*UPP WAV-VIR*
Motional Stark Effect	*Internal Magnetic Field Characteristics*	*MSE*
Core Imaging X-Ray Spectrometer	*Plasma Ion Temperature*	*CIXS*

Figure 1: There are seven US ITER diagnostic systems distributed around the upper and equatorial ports. Portions of the diagnostics are housed in port plugs and other supporting and shielding structures.



II. DELIVER DAY-ONE D-T READY SYSTEMS

It is expected that all diagnostic systems initially delivered to ITER are "D-T Ready". Design loads are based on steady-state 500 MW fusion power and 15 MA plasma current conditions. Diagnostics need to be ready for the effects of high radiation and heat flux, electromagnetic transients and requirements for tritium and high-vacuum confinement.

These requirements put unprecedented stress on the engineering design and analysis process. The ITER organization has implemented a comprehensive design review, quality and safety assurance process to control these advanced designs. Design through analysis, R&D and detailed prototypes must be performed before the system is delivered because there will not be time or budget for verification on ITER.

Every aspect of ITER diagnostic design is touched by the D-T readiness challenge. From optical performance to maintenance, some aspect of the diagnostic design requires new thinking and rigorous analysis. Table II highlights a critical D-T Ready design feature of each US diagnostic system.

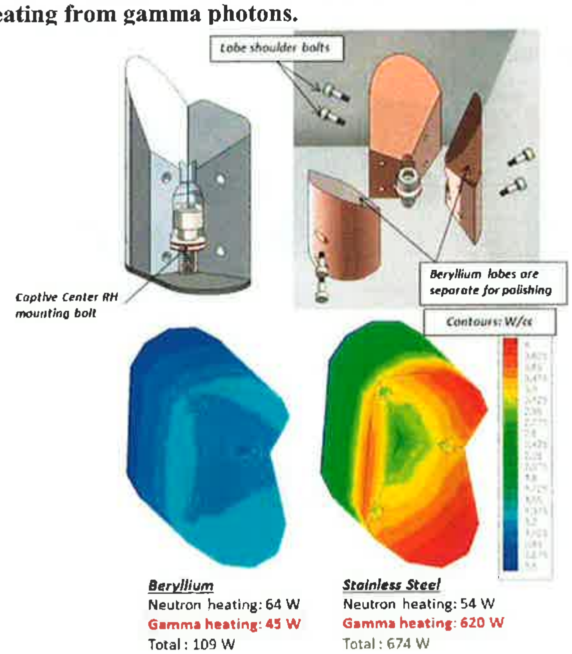
TABLE II. SAMPLE OF D-T READY FEATURES OF USDA SYSTEMS

USDA System	*D-T Ready Design Choices Unique to ITER*
DRGA	*All UHV gas sampling line components must also be tritium confinement qualified*
LFSR	*Front-End Antenna are also Water Cooled First Wall Components*
ECE	*Need to place hot calibration sources inside port plug harsh environment to optimize EP9 shielding*
TIP	*Beryllium Corner-Cube Reflectors to limit nuclear heating*
UPP WAV-VIR	*Long optical relay out to Visible and IR cameras to shield detectors behind bio-shield*
MSE	*- Carefully optimized optical labyrinth - Stray Light Mitigation*
CIXS	*Radiation Hardened X-Ray Imaging Detectors and Crystals*

A. TIP Systems Beryllium Corner Cubes

The TIP system employs corner cube reflectors embedded into blanket shield modules on the other side of the machine. The CCRs are subject to high neutron and gamma flux during D-T without access to water cooling. Distortion of the optical faces of the CCRs becomes a big problem especially with higher nuclear heating. By using Beryllium CCRs the nuclear heating in the corner cubes can be reduced by up to %80 over Stainless Steel CCRs in the same position. Figure 1 illustrates the design of the TIP CCRs as well as total nuclear heating contours for steel and beryllium.

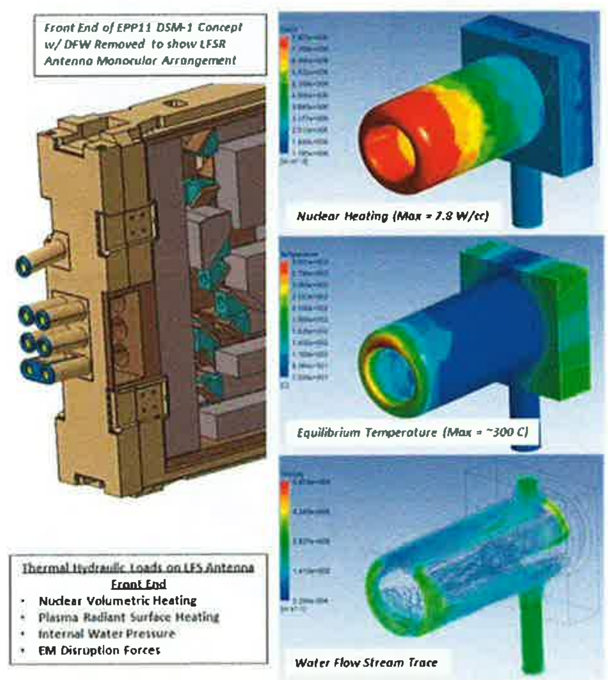
Figure 2: The TIP diagnostic corner cube reflectors are assembled from three beryllium lobes with polished front faces. Beryllium has been selected to minimize nuclear heating from gamma photons.



B. High heat-flux LFSR antenna

Another example of how D-T readiness is driving design is from the Low Field Side Reflectometer (LFSR). The USDA is trying to quickly lock in a physics design and basic system layout because the launch/receive antenna horns are also part of the diagnostic first wall. Each LFSR antenna will be heavily loaded with EM, nuclear and radiant heating which requires a lot of analysis as well as prototype items for testing. If D-T readiness was not an initial requirement alternate antenna configurations and horn designs could be tested. Figure 2 illustrates aspects of the LSFR antenna co-axial design with integral corrugations and cooling.

Figure 3: The design of the front portion of diagnostics becomes very complex once loads from full 500 MW D-T operations are considered. The LFSR antenna horns become first wall components with high radiation effects and thermal stress management. Multiphysics analysis software is used to evaluate nuclear heating (~8 W/cc max), radiant heat loads and the antenna equilibrium temperature with internal water cooling.



C. DRGA sampling pipe maintenance

Another example of how D-T readiness is driving the design of diagnostic systems is in the schemes for component maintenance. The Diagnostic RGA (DRGA) system samples the torus vacuum at Lower Port 12 and Equatorial Port 11. DRGA instrumentation is placed back in the port cell and a long sampling pipe with flanges and valves brings the torus vacuum back to the instrument. All portions of the DRGA become part of a long tritium confinement barrier and any maintenance on the DRGA requires tritium line break. The US

DRGA team is developing maintenance schemes for disconnecting the vacuum flanges at key locations in order to remove components that will likely need regular maintenance. Rather than fabricate expensive metal flanges 3D printed plastic flanges were fabricated for the maintenance mock-up exercise. Technicians enclosed the bolted flange joint in a loose fitting plastic bag. When the flanges are unbolted and separated the bag is tucked between the flanges and then cut with special hot knife. This divides the bag in to two sealed bags keeping any potential tritium or beryllium contamination inside to be handled later in a hot cell glove box.

Figure 4: ITER style vacuum flanges for the DRGA were "fabricated" in a plastic 3D printing machine. Technicians then practiced separating and bagging the flanges keeping any potential tritium contamination inside the bag. The orange gloves are also left behind in the sealed bags.

D. Elecromagnetic loads on optical components

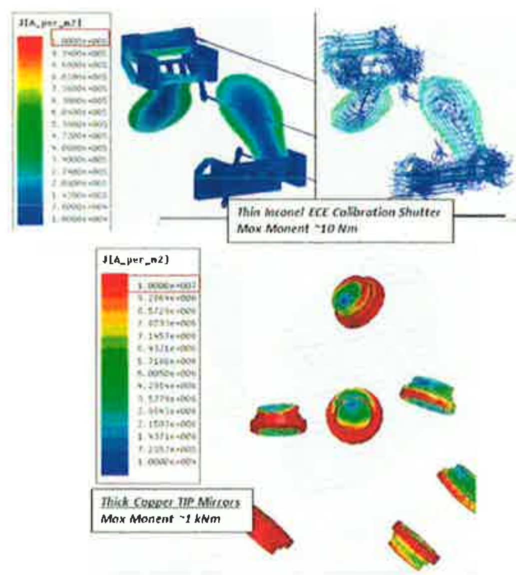
ITER diagnostic components in the port plugs will be subject to two distinct structural loads resulting from the severe plasma disruptions. The port plug structures in which the diagnostic components are mounted undergo shocks. Port Plugs are cantilevered from the vacuum vessel and oscillate violently as they are plucked by the disruption shock. Diagnostic components, which are much less massive than the port plug structures, experience high G-forces going along for the ride. The second structural load are JxB forces induced directly in the diagnostic component. Eddy currents are induced in the metal mirrors and shutters by the electromagnetic transients. Forces are then induced in the cross product of the eddy currents with static TF and PF magnetic fields of up to 4 Tesla.

Electromagnetic loads in the diagnostic ports and components can be simulated in various commercially available finite element codes. PPPL primarily uses the ANSYS product MAXWELL as well as the OPERA for cross checking results. There are many ITER plasma current and magnetic coil scenarios of varying severity and probability provided by the IO. For the diagnostic equatorial port plugs the worst case load is for a 15 MA 16 ms major disruption which induces an incredible 4.5 MNm torque on the port plug in a very short period of time. This is approximately 280 MW of mechanical twisting power.

Electromagnetic loads on the small diagnostic components are also calculated using MAXWELL or OPERA. Minimizing electromagnetic forces can be accomplished in several ways. Eddy current loops should be broken using gaps or materials with high resistivity. For example the ECE Hot Calibration source mirrors will be fabricated from Inconel. These shutters are also electrically isolated from the shield module using a ceramic pad. In combination this reduces induced currents in the shutters where the applied moment is .01 kNm.

The ECE shutters and the TIP first mirrors are subject to the same magnetic flux but the TIP mirrors are much more heavily loaded because of material and geometry. Copper is optimal for reflection of the TIP lasers and the copper discs are also thick to retain a flat reflecting surface. Whereas the ECE shutter eddy current density is only on order of 5E5 A/m^2 the TIP Copper Mirrors exhibit current densities above 1E7 A/m^2.

Figure 5: The ECE shutters and the TIP mirrors are in the same location yet exhibit very different eddy current densities.



E. Optical Labyrinth Optimization

Optical labyrinth design is a critical part of ITER diagnostic engineering. Labyrinth optimization balances maximizing photon throughput and minimizing neutron leakage. Neutron leakage is minimized to limit dose to maintenance personnel from neutron activated steel and nuclear heating in nearby TF and PR coils.

In the MSE conceptual design phase initial optical designs mainly focused on optical performance. Once neutronics calculations were performed it was clear that shielding labyrinth optimization was also needed. Figure 6 shows the initial and optimized MSE concept labyrinths. The height and placement of the vertical leg of the labyrinth in the middle of the shield module proved to be the most important design factors.

Figure 6: The optimal MSE design balanced photon and neutron throughput by locating the labyrinth vertical jog in the middle of the shield module.

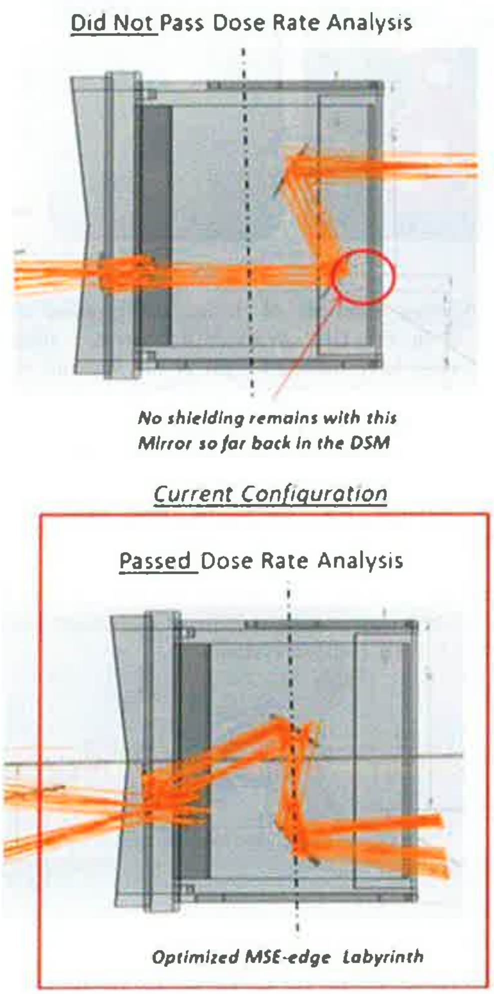
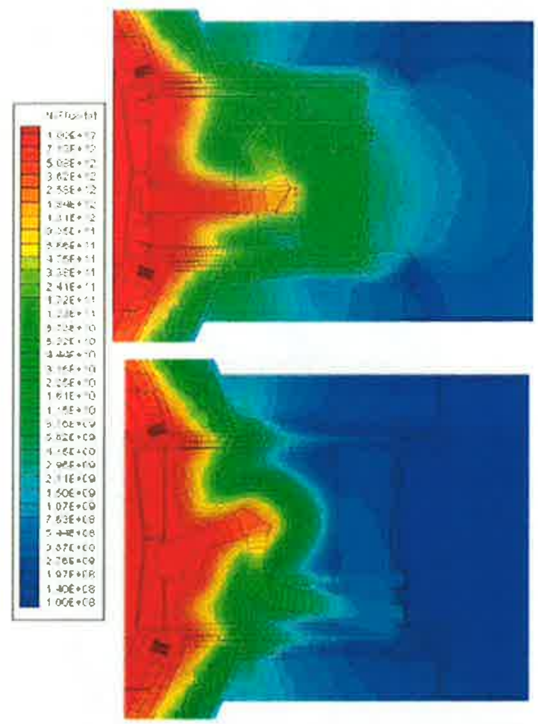


Figure 7 shows how the neutron flux through the shield module and MSE labyrinth was reduced by almost three orders of magnitude. This process of finding the best combination of optical and nuclear throughput should be done as early as possible in the system design.

Figure 7: Neutron flux at the Equatorial Port 3 closure plate was reduced by almost 3 orders of magnitude in optimizing the MSE labyrinth.



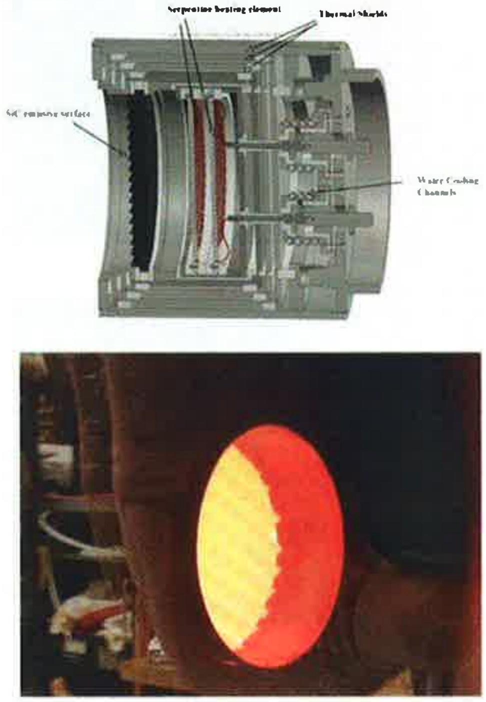
F. Design Compromise to Favor Shielding Design

D-T ready design in some cases requires hard choices to be made. Radiation protection and safety are of highest priority for ITER. Situations arise where a diagnostic component needs to be placed in a difficult environment, sacrificing maintenance access or placing the component in higher load fields, in order to maximize shielding and nuclear safety.

A good example of this is in the design of the US ECE diagnostic. The microwave diagnostic requires in-situ calibration to monitor changes in optical performance between plasma discharges. Calibration of the ECE instruments can be a lengthy process and is a function of the intensity of the in-situ calibration source. A high temperature ECE calibration source, shown in Figure 8, will used for ITER to provide the intense, uniform and broad band microwave signal. The ECE calibration source is a large aperture blackbody emitter in the microwave region (100-1000GHz) operating at over 700°C inside the ITER port plug. Electrical resistance heating elements at high temperature radiate to the back of a silicon carbide disc.

Ideally the ECE hot source would be mounted in an accessible position allowing for routine maintenance, upgrades or troubleshooting. It must be able to operate reliably for one to two days twice a year for up to 5 years without maintenance. Once D-T design rules were applied, namely the need to limit radiation coming from the port plug, it quickly became apparent this was not possible.

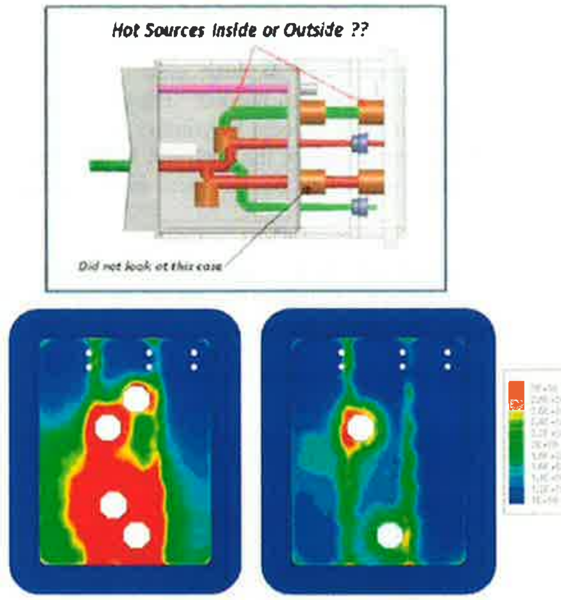
Figure 8: The ECE Hot Calibration Source uses a set of resistance heaters that radiate on to the back of a specially shaped silicon carbide disc. Temperatures in the SiC up to 700C are achieved.



Installation of the two ECE hot sources on the port closure plate requires two additional labyrinths to be formed through the crowded shield module. These additional labyrinths also prevent the two main ECE optical labyrinths from being fully optimized for shielding. Figure 9 provides ATTILA neutronics results illustrating the dramatic change in neutron flux between the two cases.

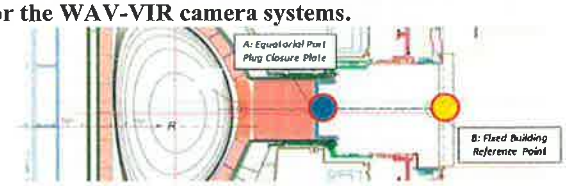
Neutrons activate the steel structures at the rear of the port plugs and surroundings. The radio isotope Cobalt-60 is produced from trace impurities in the 316LN steel. Co-60 radiates two high-energy harmful gamma photons over a long 5 plus year half-life. Experience in conceptual design has shown that a neutron flux below 3E8 n/cm2-s is needed at the rear of the port plug to achieve acceptable levels of Co-60 activation.

Figure 9: Ideally the hot sources would be mounted on the port plug closure plate for maintenance access. Neutronics results clearly showed this was not feasible because high neutron flux resulted in highly activated port plug structure steel.



Another example of design compromise to favor shielding is in the UPP WAV-VIR system. Ideally the cameras would be positioned right at the vacuum windows attached to the port plug. Radiation and bake temperatures are too high to realize this and the cameras are positioned 5 meters away behind the bio-shield wall to maximize shielding. This requires an additional set of relay optics, an additional labyrinth through the bio-shield and new alignment challenges.

Figure 10: Relative motion between the port plug and the fixed bio-shield wall creates a difficult alignment problem for the WAV-VIR camera systems.

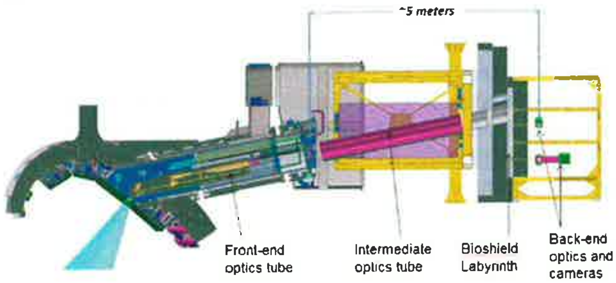


"A" will move relative to fixed "B" by:

Motion (mm)	Operating	Disruption	Bake
Radial	15	27	34
Toroidal	0	12	0
Vertical	10.5	13	27

Figure 10 illustrates how the target vacuum windows on the port plug will move relative to the CCD cameras affixed to the building behind the bio-shield. The relay optics between these two point has to be able to flex with the motion and then repeatedly return to true alignment.

Figure 11: The UPP WAV-VIR intermediate optics tube will need to be mounted such that alignment can be re-established after plasma disruptions and vacuum bake cycles.



G. Stray Light

Most of the mechanical, nuclear and optical engineering challenges discussed in this paper can be mitigated by using smaller optics and diagnostic components. Small component are also easier to package in the crowded port plugs and of course cost less. This drive towards minimizing component sizes has to be balanced with the need to have high photon throughput to bring signal strength above background and shot noise levels. On ITER this optimization of size versus throughput is complicated by very high stray light levels. Bulk Bremsstrahlung on ITER will be high in the D-T phase. Added to this is Divertor Bremsstrahlung and divertor thermal radiation [4] reflected off the high-reflectance ITER beryllium walls .

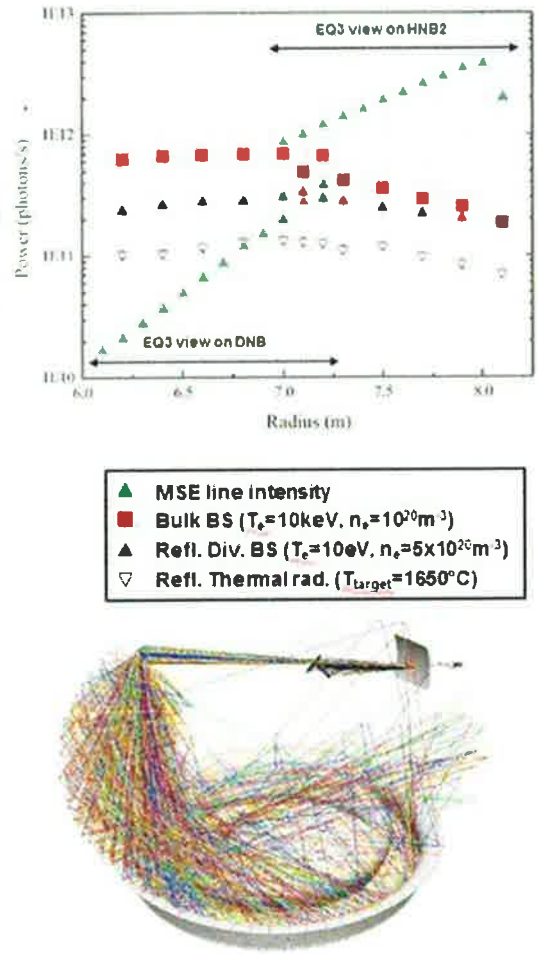
Studies for MSE show divertor stray light is approximately the same order as line integrated bulk BS intensity and up to an order of magnitude larger than the MSE line intensity in the plasma core. As the intensity of stray light increases the system signal to noise ration can only be maintained if total system throughput is also increased as can be seen in Figure 10. "T" must rise as I_{BS} and I_{STRAY} rise. The implications of this simple equations present a major challenge for engineering "D-T Ready" systems like MSE. Figure 11 illustrates the stray light challenge particularly in the Core ITER regions. Some optimal level of throughput based on the final size of MSE components will balance the need to strictly limit neutron leakage with the need to overcome background light by maximizing throughput.

Figure 12: Simple equation for signal to noise in the MSE diagnostic. Total system throughput must be increases to maintain signal to noise as stray light levels increase.

$$\text{S/N ratio} = \sqrt{T}\,\frac{I_{MSE}}{\sqrt{I_{MSE}+I_{BS}+I_{stray}}}$$

T= Total System Throughput

Figure 13: BS, reflected divertor BS and reflected divertor thermal radiation dominate MSE line density photon counts in the plasma core. Sophisticated ray tracing software was used to analyze the stray light levels for MSE as shown at the bottom of this figure.



III. Conclusion

ITER diagnostic engineering is a challenging endeavor. From machine protection to verification of plasma physics theory, there is a set of high performance ITER diagnostic systems under development to provide the data. Most ITER diagnostics are based on systems successfully deployed on existing magnetically confined fusion devices. ITER presents the new requirement that these system be "D-T Ready" upon delivery.

The first challenge of D-T operation is in nuclear engineering and shielding design. Components near the plasma like the TIP corner cubes and LFSR antenna horns need to deal with the high nuclear heating and plasma heat flux. Optical systems like MSE require carefully engineered shielding labyrinths that balance optical performance with neutron leakage. A further complicating factor is the high stray light levels on ITER during D-T operation. One way to maintain acceptable signal to noise ratios is to increase total system throughput. A labyrinth optimized for nuclear shielding also must be optimized to deal with this stray light challenge.

ITER high performance plasmas will also produce electromagnetic disruptions applying massive forces to the diagnostic components and port plug support structures. Metal mirrors for ECE and TIP are in similar positions in the ports plug but will be subject to very different forces because of material, geometry and connectivity.

Maintenance of diagnostic components also becomes much more challenging in the D-T environment. The DRGA units will need to be occasionally removed for maintenance but this will require a break of confinement barriers. Procedures for bagging and sealing the end flanges are part of current DRGA prototype activities. Tough trade-off decisions are also needed in D-T design. The ECE hot calibration sources may also need maintenance but had to be placed in high radiation, high-shock inaccessible positions. This is because radiation protection and safety takes the highest importance on ITER. Placing the hot sources in an accessible position would allow too much radiation to leak out of the port plug.

There are 50 diagnostic systems on ITER facing these challenges. Physicists and engineers from the seven ITER member domestic agencies and the ITER central team are working together to share innovative ideas, reduce redundancy and achieve world class diagnostic systems. Expenditures in detailed prototypes and complex analysis are needed to simulate the ITER environment in order to deliver D-T ready diagnostics.

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The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

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