A collaboration opportunity for next step tokamaks: ITER and DEMO
(specifically a next generation diagnostic: the pulsed polarimetry technique)

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Area: Diagnostics for future burning tokamak devices and stellarators.

Benefit: An opportunity to develop compelling technology in the area of plasma diagnostics allowing *internal* field, n_e and T_e measurements on next step tokamaks and stellarators.

Questions:
1) What can the US do in regards to ITER and DEMO to allow us to be an integral player, to play a bigger role?

2) Our importance within international MFE science is only as strong as our domestic MFE expertise and, as argued below, by any special techniques we can bring to the table. Can we continue our pre-eminence in plasma diagnostics as MFE matures to reactors?

The US has not assumed a key role in the design and operation of ITER or DEMO, for those responsibilities, Europe has taken the lead. The US is playing an important role in implementing key diagnostics on ITER such as the mid-plane tangential interferometer/polarimeter and MSE diagnostics, to name two, diagnostics that the US was instrumental in developing. Our presence on ITER will be mainly through the territory staked out by our diagnostics and DEMO, perhaps the same. It has often been expressed that progress in magnetic confinement goes hand-in-hand with diagnostic development. The purpose of this white paper is to bring forth a new and developing diagnostic technique and propose it to the FESAC International Collaboration Panel as a topic for collaborative international research. The diagnostic is a remote sensing technique with potential for measuring internal magnetic field distributions, i.e. the *local* magnetic field on ITER plasmas and improves in this regard on DEMO. Its measurement capabilities encompass those of Lidar Thomson scattering (*local* n_e and T_e) and polarimetry and the MSE technique so that the development is of international interest and import. The diagnostic improves with device performance (higher parameters) and provides an important new field measurement capability in a context where other diagnostics are failing.

Existing diagnostics within the magnetic fusion community are struggling to find purchase on ITER let alone DEMO. The International ITER diagnostic program should have a two fold purpose, **1)** most importantly, to achieve a successful ITER program through device protection, operation/performance and physics discovery but also **2)** to lay the foundation for diagnosing future fusion reactors. Most assuredly, DEMO and all future engineering reactors will require diagnostics to operate successfully. In this light, one might ask which diagnostics are merely bridging a gap to DEMO on ITER and which diagnostics can be advanced and developed through ITER which will also apply to DEMO? The pulsed polarimetry technique has strong potential for DEMO, that is, the technique combines the best advantages of any remote sensing Lidar technique given the problems posed by a burning plasma. *A change in the ITER diagnostics is not advocated here* only that an investment in promising diagnostics for DEMO be initiated. And through that development, an integral role for the US may be assured on DEMO.

Addendum

The pulsed polarimetry technique generalizes Lidar Thomson scattering (TS) by taking advantage of the magneto-optical activity of a magnetized plasma (Faraday and Cotton Mouton (CM) effects) for the remote sensing of the *local* magnetic field. This necessitates implementing Lidar TS in the far infrared (50 to 200 μm) wavelengths. Lidar TS on ITER is being developed in the NIR (1 μm) to mitigate the problem of first mirror degradation in the visible. A question to pose is: why not a 10 μm system using a CO_2 laser? The required laser is extant and one might balk at the detector issues but there are choices there too. It is doubtful that a 1 μm system will be adequate on DEMO. It may suffice for ITER, represents an incremental change over JET's Lidar system but achieves only a modest step of robustness for future burning plasmas. A Lidar TS system at longer wavelengths seems necessary for the future challenges. The other important diagnostics that pulsed polarimetry touches on (polarimetry and MSE) are not even that fortunate.

Polarimetry systems require retro-reflectors (fixed sightlines) and are susceptible to refraction. Pulsed polarimetry eliminates retro-reflectors and is not bothered by refraction. But pulsed polarimetry's most compelling advantage is the remote sensing of the $[n_eB_{||}]$ product through the Faraday effect which yields a *local* determination of $B_{||}$. This also applies to the $[n_eB_\perp^2]$ product through the CM effect which allows a more complete unfolding of the magnetic field's $(\mathbf{B}_\perp,B_{||})$ spatial distribution and magnetic shear for a mid-plane sightline. If polarimetry, as presently conceived, has no future on DEMO what magnetic sensing diagnostics are left?

The motional Stark effect diagnostic measures the *local* magnetic field or field shear given the strong toroidal field specific to tokamaks. There are three problems to note, **1)** a particle beam is required which will be difficult on DEMO, **2)** MSE is an atomic radiation based technique and **3)** the technique necessarily uses visible wavelengths. Atomic radiation based diagnostics suffer signal-to-noise issues that are hard to overcome (background plasma light, intensity limitations, population depletion), laser aided techniques, on the other hand, can in principle buy their way out of trouble with a stronger laser or modulating the laser, as is done for collective TS (amplitude modulation). This is leading to a MSE-LIF laser induced fluorescence technique but the fundamental problems of MSE remain. It is doubtful that MSE will be a DEMO diagnostic.

The pulsed polarimetry method has not yet been confirmed experimentally but seems not to be in doubt, being a combination of TS and polarimetry, one could argue, two of the most widely used and best understood plasma diagnostic techniques. Lidar TS is a difficult technique since ultra-short, powerful lasers and ultra-wide bandwidth detectors are needed. One might argue that the JET Lidar system has not been much improved in the last two decades, what chance would a FIR Lidar system have? But ITER and DEMO, because of their size, ameliorate much of this concern. The detectors are only required to have ~nanosecond time response; the detector size can be accommodated by using arrays of detectors and solid state detectors arrays are approaching 50 μm wavelengths(QWIPs). The FIR laser pulses can be produced using extant powerful, ultra-short pulsed CO_2 lasers and pulse bandwidths can be obtained either through the bandwidth of the FIR medium or by pulse slicing the output. There are challenges to bring this technique to fruition and focused research is needed but the required technologies are mostly developed. For instance, powerful FIR sources were being developed in the 70's for fusion research but the focus changed to gyrotrons, once they were shown to have high output powers.

Pulsed polarimetry (PP) is such a compelling technique for the following reasons. PP 'completes' refractive index diagnostics since *local* sightline T_e is measured and 'finite T_e'

effects can be corrected for. Line integrated interferometry/polarimetry measurements are subject to the same corrections without having the knowledge of sightline T_e. PP is an aim-and-shoot diagnostic, sightlines can be mid-plane, off mid-plane, into the divertor or oblique (tangential). Diagnostic integration is high, T_e, n_e, $B_{\|}$, $\boldsymbol{B}_{\perp}$ distributions are obtained, all through one port. The longest wavelengths are used, so mirror degradation is minimized. Every chord gives T_e and n_e profiles along with magnetic profile information. The FIR wavelengths imply that all measurement sensitivities: n_e, T_e and B are similarly high. Large changes in polarization are produced and measured with high resolution. Machine protection is a key element of PP as MHD instabilities can be, not only detected in time but also localized in space which would aid advanced tokamak scenarios which seek to modify the plasma current profile to eliminate the instability. PP can enhance machine operation/performance as local field profiles are the most germane diagnostic input for equilibrium fitting and the use of multi-chord inversion using line integrated data is considerably improved upon. Most importantly, pulsed polarimetry improves (becomes easier) with higher n_e, B_{pol} and machine size with respect to sensitivity, spatial resolution, wavelength range and bandwidth.

This is not to say, a FIR pulsed polarimeter would be easy to develop, those diagnostics, such as interferometry, have long been exploited as a plasma diagnostics. Pulsed polarimetry would require a collaborative effort of laser, detector and plasma specialists, preferably an international collaboration since the technique touches on many diagnostic systems, not all of which are US ITER diagnostics. A CO_2 version could be produced and fielded on many existing machines, JET, Asdex-upgrade, DIII-D providing a platform for an FIR version and at the same time giving the plasma community a 10 μm Lidar TS system. So magnetic field sensing on DEMO is not dismal at all. As inboard magnetic sensing using electrical probes or laser polarimetry becomes impractical, pulsed polarimetry provides an attractive alternative on DEMO. In addition, advancing Lidar techniques into the FIR domain is a wide open technology for the remote sensing of molecular species and chemistry in the Earth's atmosphere and detector development in the FIR region is a strong and burgeoning field for FIR astronomy. A US and international investment in this technology would be well compensated on many fronts and give the US a key presence throughout the future MFE program.