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ABSTRACT

The next generation of tokamaks present unique challenges to plasma diagnostic design due to the physical size of the devices and the radiation environment. The need for a density measurement for density feedback control for a prototype reactor such as ITER is well established and several proposals for line average measurements have been put forward.[1,2] In this paper, a design for a line average density diagnostic for ITER using collinear interferometry and Faraday rotation measurements will be presented. Plasma effects on both types of measurements and density resolution and will be discussed along with the possibility of combining the information from the two collinear measurements to improve the reliability and quality of the density profile. Survivability of the plasma facing mirrors, in particular the surface flatness and surface roughness, are critical issues and preliminary analysis suggests these may limit the wavelength of probing beams. Thermal and stress analysis of the plasma facing mirrors will be presented along with a discussion of mirror material selection based on thermal, nuclear and sputtering considerations.

I. DIAGNOSTIC LAYOUT

The access on ITER will be severely constrained. Besides the usual access limitations resulting from the toroidal geometry of a tokamak, ITER will have further restrictions due to the nuclear environment. Shielding of the various liquid He-cooled coils, the overall volume of shielding, and the vast water cooling lines required for the shielding occupy much of the space near the tokamak and will limit port access. In the present design, port access is limited to vertical, radial and tangential views. Vertical access in ITER is problematic in that the port access design philosophy centers around the large radial ports, and access through the various layers of the ITER device, including the vacuum vessel, cryogenic vessel and biological shield, are by far simplest through the radial port extensions. Some small vertical ports at the top of ITER may be made available for diagnostic use but access to the ports through the cryostat is very difficult and there are no vertical ports in the bottom of ITER. Radial sight lines would require a reflecting surface to be mounted on the inside wall. An embedded retroreflector may survive, (Section V) however, the neutron streaming into the coils in the centerpost through the penetration cause unacceptable local heating in the coils. It may be possible to use the undisturbed inner wall as a reflecting surface, although this limits the number of lines of sight to nearly one and also limits the probing beam wavelength to perhaps unacceptably long wavelengths. (See Section III.)

Tangential sight lines as shown in Fig. 1 represent little technical risk, provide a good set of density monitors and have minimal impact on the rest of the ITER device. As shown there is no impact at all on the shield modules as all of the diagnostic optics are located in port modules. The retroreflectors shown in the port plugs are relatively small (roughly 10 cm diameter or 1% of the port area) but may still be difficult to locate. Another option is to locate the retroreflectors in the shield modules in between the ports. Putting the retroflectors in the shield modules makes those shield modules unique and more costly and also makes maintenance on the retroreflectors much more difficult (although we expect the retroreflectors to survive the life of the shield modules). In either case there is no fundamental problem with the layout of a multi-channel set of tangential lines of sight.

Density control of the plasma is required very early in the formation of a ITER plasma. Figure 2 shows cross sections of the startup phase of an ITER plasma along with the proposed tangential sight lines (the points shown are the points of tangency of each sight line).[3] A line average density with sampling very near the center of the plasma is possible from plasma break down as long as the density lines of sight are near the bottom of the radial ports.

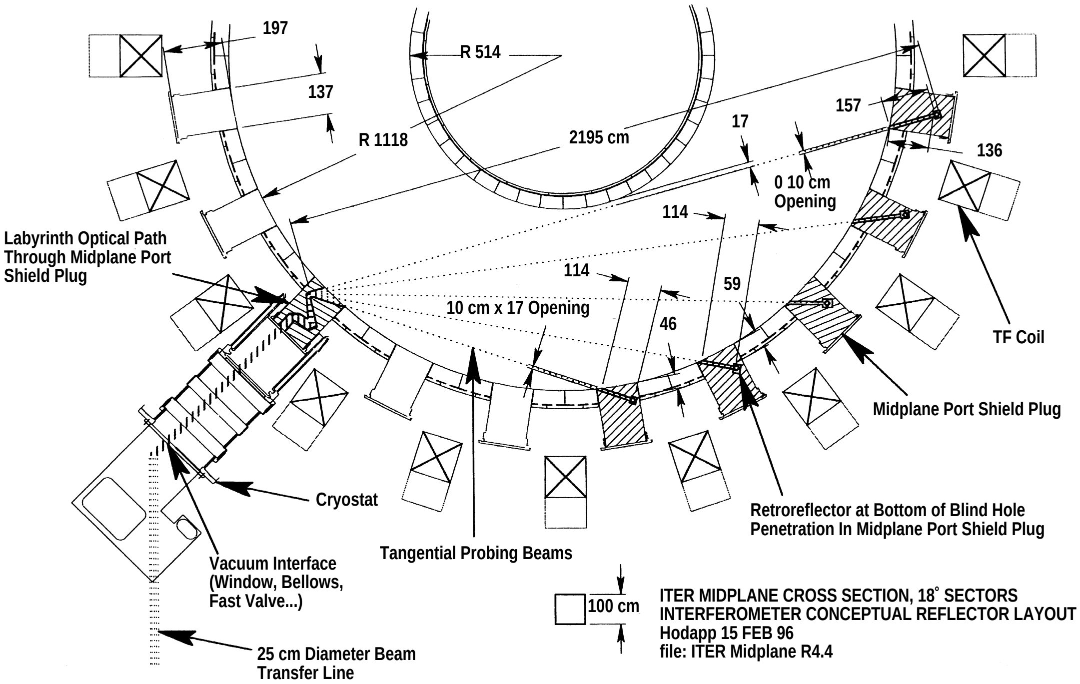

Fig. 1. Layout of a tangential array of lines of sight for an interferometer on ITER with all of the optics enbedded in port plugs.

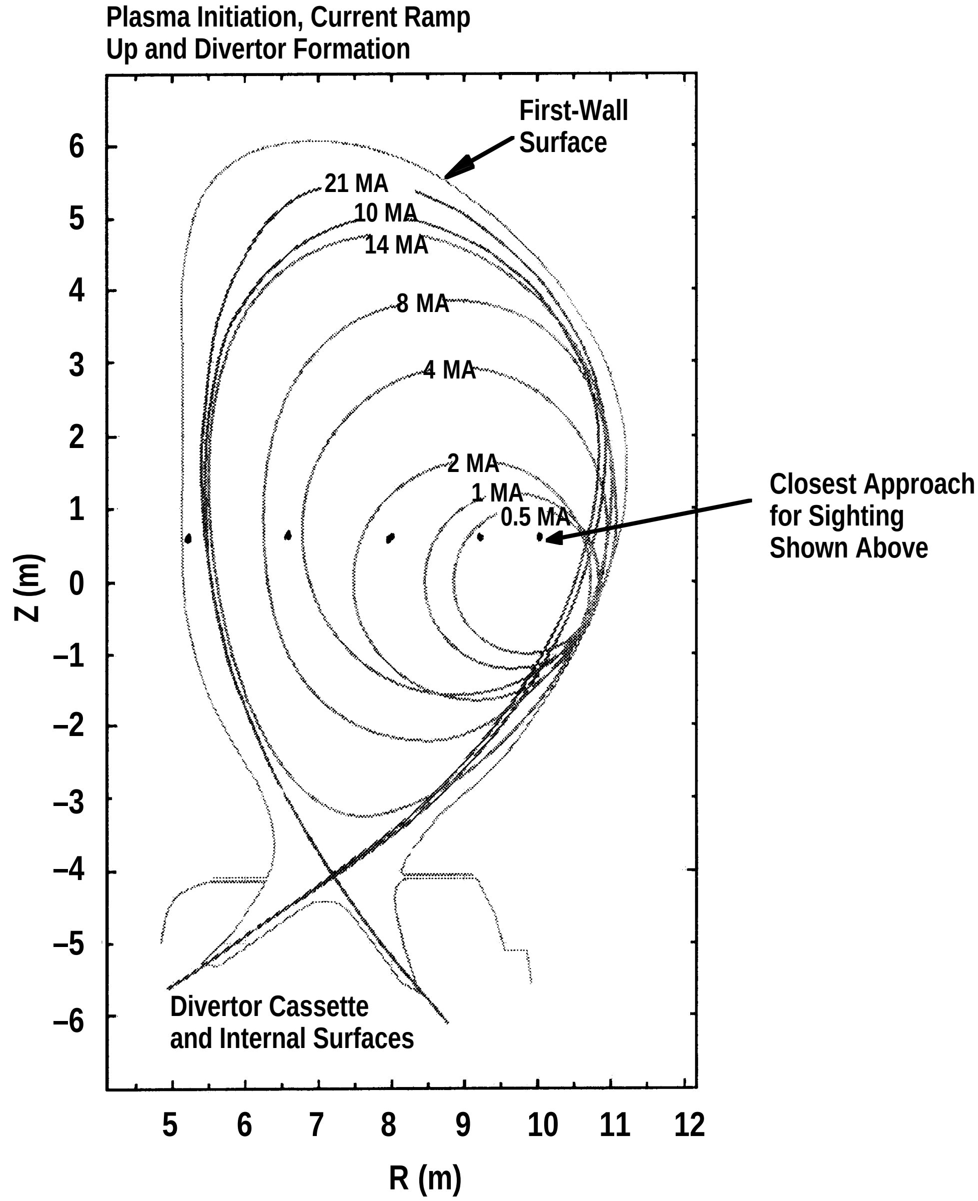

Fig. 2. Plasma cross sections for ITER plasma initiation, current rampup and divertor formation. The points along the midplane are the points of tangency of the lines of sight shown in Fig. 1.

II. DENSITY MEASUREMENT TECHNIQUES

Laser interferometry is a well established method for measuring electron density in high temperature plasmas. In a high temperature plasma the change in the refractive index is dominated by the electrons and, in a tokamak plasma can cause significant displacement, deflection and phase lag of a probing beam. A measurement of the phase lag caused by the electron density (n_e) is used to infer the line average density and is proportional to λ. Mechanical motion of the mirrors in the direction of beam propagation also produce phase shifts ($\Delta\phi = 2\pi\ \Delta/\lambda$; where Δ is the change in path length due to the motion) in the plasma probing beam. Vibration isolation structures are impractical on a machine the size of ITER, particularly with the restricted port access. A second wavelength interferometer can be used to compensate for any motion of the optical components.[4] This allows the optical components, such as the retroreflectors and relay mirrors, to be directly mounted onto the vacuum vessel or port structures. However the density resolution (for a given phase resolution) of the system is reduced proportionally to approximately the difference in the two wavelengths. If the phase lag caused by the electron density and the mechanical motion is larger then 2π then the time history of the phase throughout the discharge is needed to determine n_e, and any loss of the time integral of the phase shifts during the discharge results in a loss of the density measurement. Because of the mechanical motion of the optics in ITER, the total phase measured will be much larger then 2π for any relevant wavelength.

A measurement of the Faraday rotation of a probing beam that is tangential to the toroidal field at the midplane can also be used to monitor the plasma density. First proposed by Jobes,[1] this technique has several advantages over interferometry. The measurement does not depend on the past history of the plasma discharge as long as the rotation is less than 2π (the absolute measurement of the Faraday rotation is all that is required) and vibration of the optics do not effect the measurement. Because vibrations do not add to the polarization rotation a wavelength can behave such that the total polarization rotation is less 2π for all ITER discharges. A linearly polarized beam propagating in the direction of the magnetic field experiences a rotation in the polarization of $\Phi \propto \lambda^2 \int n_e \mathbf{B} \bullet \mathbf{d}\ell$. At the midplane the magnetic field is approximately the externally applied toroidal field (B_T) which can be measured accurately with standard magnetic diagnostics so that a density measurement can be extracted from Φ if an Abel inversion is performed on a multi-channel system. The actual field along the line of sight is different than $\mathbf{B}_T \bullet \mathbf{d}\ell$ due to contributions from the poloidal field when the beam is off midplane and from diamagnetic and paramagnetic effects from the plasma. The poloidal field contribution is small, axisymmetric, with offsetting contributions from either side of the tangency point and will cancel and will not cause a significant error (Fig. 3). The finite plasma pressure and the finite poloidal current in a tokamak causes a change in

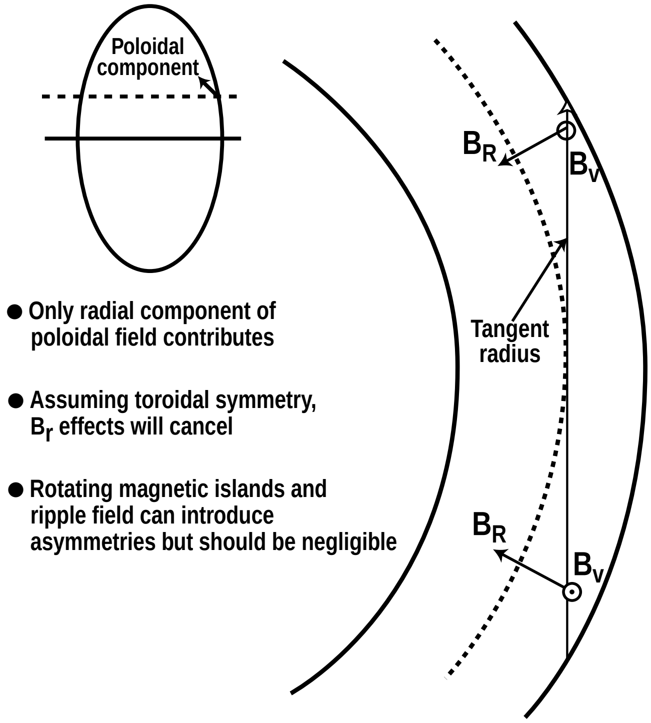

Fig. 3. The effect on $n_e\,\mathbf{B}\bullet\mathbf{d}\ell$ propagation above midplane in tokamak plasma concepts.

the toroidal field that will, in principle, affect the accuracy of the inferred density measurement. The local change in the toroidal field (B_ϕ) can be calculated from the expression for the change in flux

$$\int_0^r \Delta B_\phi(r')r'dr' \propto \frac{I^2(r')}{B_T(r)}\left[1-\beta_p(r)\right] \quad ,$$

where I(r) is the enclosed toroidal plasma current at r and

$$\beta_p(r) = \frac{16\pi^2 k}{\mu_0 I(r)^2}\int_0^r p(r')r'dr' \quad ,$$

where p(r) is the total pressure. We have calculated this effect for ITER using profiles (J, n, T) of the form $(1 - r^2/a^2)^\alpha$ with $\alpha = 0.5$ to 3, $I_p =$ 2–21 MA, $n_D = 10^{19}$–$10^{14}/m^3$, T = 2–10 keV, and found that the correction in $\int n_e \mathbf{B}_T \bullet \mathbf{d}\ell$ is of the order of 2% or less. While this correction is small enough to be ignored for a density measurement, it does offer the intriguing possibility of a internal measurement of the toroidal field and thus an internal measurement of the total pressure including alpha particles. In order to consider such a measurement a significant increase in the polarization resolution that can be measured would be required.

The tangential geometry proposed for a density measurement on ITER allows the possibility of making both an interferometer measurement and the Faraday rotation measurement using the same optics and indeed the same laser beam. Further the measurements are complementary in that the interferometer for a given wavelength has better density resolution (based on the current demonstrated detector technology coupled with the complication of unfolding the toroidal field in the Faraday rotation measurement) while the Faraday rotation does not necessarily have the long pulse problem of keeping track of fringe shifts.

III. PROBING BEAM WAVELENGTH CONSIDERATIONS

A. Plasma effects

The large physical size and high plasma density of ITER restrict the use of long wavelength probing beams due to refraction and diffraction effects. On the other hand, density resolution, mechanical vibrations, and the impact on the optical surface quality of plasma facing optics from the harsh environment of ITER restrict the use of very short wave lengths.

The refractive bending of a tangential probing beam results in a translation of the beam at the return retroreflector that is approximately proportional to $n_e\lambda$ for small deviations and peak displacement is roughly independent of the density profile shape.[2] The divergence of the probing beam determines the spot size of the beam at the retroreflector. For the spot size that contains 95% of the power is given by $d_r = 2\sqrt{2}\,n(\lambda z/\pi)^{1/2}$ while the return beam spot size at the exit port (d_w) will be $\sqrt{2}$ larger. Table 1. lists the shield penetration size for both the retroreflector and the entrance/exit mirror for various wavelengths based on the refraction and defraction effects. The penetration sizes become excessive at wavelengths longer then 50 μm.

Also listed in Table 1 are the total phase shifts and Faraday rotation angles for both high density and low density plasmas in ITER. While reasonable density resolution can be achieved with a wavelength as low as 1 μm using interferometry the Faraday rotation measurement becomes

Table 1, Summary of relevant parameters for various wavelenths for a tangential double pass beam in ITER

d_r is the retroreflector diameter, d_W is the exit/entrance port diameter, ϕ is the phase shift due to the plasma density, Φ is the polarization rotation due to Faraday rotation in the plasma.

λ (μm)	d_r/d_W (cm)	$n_e(o)$ (x 10^{19} m^{-3})	ϕ (rad)	Φ (rad)
195	74/91	13	1969	73
		1	151	5.6
119	44/57	13	1202	27
		1	92	2.1
50	22/30	13	505	4.8
		1	39	0.37
10.6	10/13	13	107	0.21
		1	8	0.016
3.39	6/8	13	34	0.022
		1	2.6	0.017
1	3/4	13	10	0.0019
		1	0.78	0.0005

useless for wavelengths shorter than 10 µm. A more serious concern for the use of wavelengths of 1 µm or shorter is the optical quality of the plasma facing mirrors. The mirrors as shown in Fig. 1 are relatively close to the plasma and as will be shown in Section V distortion due to nuclear heating can becomes a serious problem for wavelengths much shorter then 10 µm. Our conclusion is that an appropriate choice of wavelengths for the system shown in Fig. 1. should fall between 2 µm and 20 µm.

B. Choice of lasers

There are a number of possible combination of lasers that could be made to work in the wavelength region of 2 µm to 20 µm. Clearly a system based around a CO_2 10.6 µm laser would be the optimal since very large power commercial lasers are readily available and several systems have been routinely used on existing tokamaks.[5,6] If we use as the primary laser line 10.6 µm and restrict the second laser required for the interferometry to wavelengths less then 10.6 µm and longer then say 3.39 µm, then the beam path optics, including all of the portion of the diagnostic that interfaces with ITER can be designed without specifying the exact laser combination. At least four separate laser combinations have been proposed that meet the above requirements, each with advantages and drawbacks, but each could be made to work using the same optics path.

A CO_2 (10.6 µm) and a Infrared HeNe (3.39 µm) system has been demonstrated on the DIII–D tokamak with good results,[2] the main drawback for ITER is the low power available in the HeNe lasers and the relatively short wavelength of the HeNe.

On JT-60U a system using two CO_2 lines (10.6 µm and 9.5 µm) has been demonstrated,[7] this system has the advantage that the power available in the two CO_2 lines is large and that the wavelengths are relatively long (compared to 3.39 µm). The disadvantage of the two wavelength CO_2 system is that since the two wavelengths are very close together the density resolution is very poor for a given phase resolution as compared to a system with the wavelengths are well separated. The JT-60U team is working on significant improvements in phase resolution. If they are successful the dual CO_2 system would be a very good choice for ITER.

Two other possibilities are a CO_2 (10.6 μm) laser with a CO (5 μm) laser[6] or doubling the CO_2 laser to 5.3 μm. In both cases high powers are possible and the density resolution with current techniques is very good. However both require some development and further demonstration on an existing tokamak.

V. PLASMA FACING OPTICS AND NUCLEAR RADIATION EFFECTS

A primary concern for any optical diagnostic in a reactor environment is the survivability of the plasma facing components. In the case of the density monitor diagnostic shown in Fig. 1 the optical components will be required to maintain flatness across the entire optical surface of roughly $\lambda/4$ or about 1 μm (somewhat dependent on the exact wavelengths chosen although at 1 μm, any of the wavelength combinations discussed in Section IV can be made to work) and surface roughness less then $\lambda/4$. The important optical plasma facing components are the retroreflectors and the large flat mirror in the entrance/exit port shown in Fig. 1. Distortion of the mirrors from thermal stress caused by nuclear heating (distributed throughout the material) and plasma radiation heating (localized to the surface viewing the plasma) is the most important large scale effect on the surface flatness. Listed in Table 2 are the expected nuclear volume heating and radiation heat flux at the location of the entrance/exit flat mirror shown in Fig. 1. Because of the long pulse discharges in ITER (1000s) and the high heat loads, active cooling of all of the plasma facing reflectors is required and must be included in thermal distortion analysis. Using the COSMOS v1.71 finite element code,[8] A detailed thermal analysis was performed on conceptual designs of the retroreflectors and the entrance/exit mirror for the ITER conditions and locations shown in Fig. 1. An internally-cooled 17 cm diameter

Table 2, Distortion results from thermal analysis of internally-cooled flat mirror of diameter 17 cm from Fig. 1. Column 1 mirror material, Column 2 coefficient of thermal expansion (CTE), Column 3 thermal conductivity (K), Column 4 volumetric nuclear heating, Column 5 distortion of mirror (δ_r).

Mirror Material	CTE (m/m-K × 10^6)	k (W/m-K)	q_{vol}* (W/cm^3)	δ_r (μm)
W	4.5	167	5.9	3.5
Mo	49	146	6.0	4.4
Cu	18	391	3.2	4.7
Al	24	220	1.1	9.1
N	15	90.7	4.6	19.5
V	8.6	30.7	1.5	25
Al_2O_3	82	25	2.4	32
Ti	95	21.9	1.5	39
SS 304	17	10.3	2.1	100
In 625	13	10	2.5	129

*Radiation heat flux = 10 W/cm^2.

entrance/exit mirror was analyzed. The internal cooling consist of three coaxial passages each at a different diameter. The thermal distortion results are listed in Column 5 of Table 2 for several candidate materials and shows that the surface flatness is between 3.5 and 4.7 μm for tungsten, molybdenum and copper. The mirror design that was analyzed was conceptually very simple and there are very straightforward design changes that can be made to reduce the distortion below 1 μm. For example, separate 8.5 cm diameter entrance and exit mirrors can reduce the thermal distortion by a factor of 4 and improved shielding can reduce it by a factor of 1.5 to 3.

A one piece tungsten retroreflector with non-uniform external cooling was also analyzed. The non-uniform external cooling consist of a single tube brazed to each orthogonal side. A surface flatness of 6 μm was calculated for this retroreflector configuration. In this case, internal cooling and some improvement in shielding should reduce the thermal distortion by factors of 2 to 4 and 1.2 to 2, respectively. For both mirror types we are confident that W, Cu or Mo mirrors with relatively simple design changes can be made that will reduce the thermal distortion to acceptable levels.

Sputtering of the surface by neutral particles from the plasma should produce surface roughness much less than 1 μm during the life of ITER for tungsten, copper or molybdenum based on calculations done recently by Mayer,[9] although detailed calculations for the specific geometry used on the final ITER interferometer must be done. Although there is not definitive data on plasma coating of surfaces at the midplane of tokamaks, experience on DIII–D indicates that if the optical surfaces are recessed more then 1 or 2 diameters of the penetration then coating is not a problem for wavelengths in the infrared. A study of this issue should be undertaken in existing tokamaks before we can be certain that plasma coating is not a problem for this design in ITER.

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