Polarimetry

L. Giudicotti

Consorzio RFX, Associazione EURATOM-ENEA sulla Fusione,
Corso Stati Uniti 4, 35127 Padova, Italy

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Polarization of EM waves

The electric field of a plane, monocromatic, polarized EM wave frequency $\omega$ propagating in the $z$ direction:

$$E_x = E_{0x} \cos(\omega t - kz + \delta_x)$$
$$E_y = E_{0y} \cos(\omega t - kz + \delta_y)$$

The tip of the electric field describes the polarization ellipse

Figure 3.1.1. The polarization ellipse of the electric field vector. At any point along a beam of polarized light, the endpoint of the electric field vector traces an ellipse in a plane perpendicular to the beam.
Polarization of EM waves (2)

The polarization ellipse can be described by the two angles $\psi$ and $\chi$

\[
\tan 2\psi = \frac{2E_{0x}E_{0y}}{E_{ox}^2 - E_{oy}^2}\cos(\delta_y - \delta_x)
\]

\[
\sin 2\chi = \frac{2E_{0x}E_{0y}}{E_{ox}^2 + E_{oy}^2}\sin(\delta_y - \delta_x)
\]

\[
0 \leq \psi \leq \pi
\]

\[-\pi/4 \leq \chi \leq \pi/4\]

These forms the reduced Stokes vector $s$

\[
s = \begin{pmatrix} s_1 \\ s_2 \\ s_3 \end{pmatrix} = \begin{pmatrix} \cos 2\chi \cos 2\psi \\ \cos 2\chi \sin 2\psi \\ \sin 2\chi \end{pmatrix}
\]

\[
|s| = \sqrt{s_1^2 + s_2^2 + s_3^2} = 1
\]

\[
\varepsilon = \frac{|s_3|}{1 + \sqrt{1 - s_3^2}} \quad \text{ellipticity}
\]
The Poincaré sphere

The Poincarè sphere gives a geometrical representation of $s$

![Diagram of the Poincaré sphere]

\[ \psi = \frac{1}{2} \arctan \left( \frac{s_2}{s_1} \right) \]

\[ \chi = \frac{1}{2} \arcsin (s_3) \]

For linear polarization states $s$ is in the equatorial plane.
The sphere poles represent right and left circular polarization states.
P represents general elliptical polarization state.

Changes of the polarization state of the beam are represented by rotations of $s$ on the sphere surface.
The 4 dimensional Stokes vector

The more general radiation beam is represented by the 4-elements full Stokes vector $S$

$$S = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = S_0 \begin{pmatrix} 1 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix}$$

$S_0$ is the intensity of the radiation ($S_0 > 0$)

$$P = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$

$P$ is the degree of polarization ($0 < P < 1$)

$s$ is used when the intensity and the degree of polarization are constant during the propagation (as in the plasma)

$S$ is necessary when the radiation is partially polarized or the intensity or degree of polarization changes during propagation
### Examples of Stokes vectors

Consider a radiation beam with unit intensity:

- Linear polarization:
  - Horizontal (+):
    - Polarization vector: \[
    \begin{pmatrix}
    1 \\
    \pm 1 \\
    0 \\
    0
    \end{pmatrix}
    \]
  - Vertical (-):
    - Polarization vector: \[
    \begin{pmatrix}
    1 \\
    0 \\
    \pm 1 \\
    0
    \end{pmatrix}
    \]

- Linear polarization at ± 45°:
  - Polarization vector: \[
    \begin{pmatrix}
    1 \\
    0 \\
    \pm 1 \\
    0
    \end{pmatrix}
    \]

- Circular polarization:
  - Right (+):
    - Polarization vector: \[
    \begin{pmatrix}
    1 \\
    0 \\
    0 \\
    \pm 1
    \end{pmatrix}
    \]
  - Left (-):
    - Polarization vector: \[
    \begin{pmatrix}
    1 \\
    0 \\
    0 \\
    \pm 1
    \end{pmatrix}
    \]

- Unpolarized light (\( P = 0 \)):
  - Polarization vector: \[
    \begin{pmatrix}
    1 \\
    0 \\
    0 \\
    0
    \end{pmatrix}
    \]

The Stokes parameters express the time correlation between the two components of \( E \) (Coherency matrix): \[
S = \begin{pmatrix}
\langle E_x E_x^* \rangle + \langle E_y E_y^* \rangle \\
\langle E_x E_x^* \rangle - \langle E_y E_y^* \rangle \\
\langle E_x E_y^* \rangle + \langle E_y E_x^* \rangle \\
i \left( \langle E_x E_y^* \rangle - \langle E_y E_x^* \rangle \right)
\end{pmatrix}
\]
The Mueller calculus (1)

The effects on the polarization state of a beam by an optical component or medium is described by the 4x4 Mueller matrix

\[ S_{out} = M \cdot S_{in} \]

\[ S_{out} = M_3 \cdot M_2 \cdot M_1 \cdot S_{in} \]

beam traverses a single element

beam traverses elements 1, 2 and 3 in series (always right to left in the formula)

Mueller matrix of a linear polarizer with axis at \( \theta \)

\[
\begin{pmatrix}
1 & \cos 2\theta & \sin 2\theta & 0 \\
\cos 2\theta & \cos^2 2\theta & \sin 2\theta \cos 2\theta & 0 \\
\sin 2\theta & \sin 2\theta \cos 2\theta & \sin^2 2\theta & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
\]

Mueller matrix of a quarter-wave plate (\( \pi/2 \) retarder) with axis at \( \gamma \)

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos^2 2\gamma & \sin 2\gamma \cos 2\gamma & -\sin 2\gamma \\
0 & \sin 2\gamma \cos 2\gamma & \sin^2 2\gamma & \cos 2\gamma \\
0 & \sin 2\gamma & -\cos 2\gamma & 0
\end{pmatrix}
\]
The Mueller calculus (2)

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos 4\gamma & \sin 4\gamma & 0 \\
0 & \sin 4\gamma & -\cos 4\gamma & 0 \\
0 & 0 & 0 & -1
\end{pmatrix}
\]

Mueller matrix of a half-wave plate (\(\pi\) retarder) with axis at \(\gamma\)

Two important properties:

When a radiation beam is detected the output signal from a detector is described by the \(S_0\) parameter of the Stoke vector (the beam intensity)

\[S_{out} = M \cdot S_{in} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}\]

Incoherent superposition of two beams with Stokes vectors \(S_1\) and \(S_2\) is described by the sum of the two Stokes vectors.

\[S = S^1 + S^2\]

N. B. Stokes vector and Mueller calculus not suitable to simply describe the coherent superposition (interference) of two beams.
Propagation in a plasma

Propagation in a anisotropic medium with characteristics refractive indexes $n_1$ and $n_2$ (slow and fast, $n_1 > n_2$) is described by the evolution equation

$$\frac{ds(z)}{dz} = \boldsymbol{\Omega} \times s(z)$$

This equation represents an (infinitesimal) rotation of $s$ on the Poincare’ sphere about the vector $\boldsymbol{\Omega}$. This is defined by the polarization states of the two characteristic waves (orthogonal).

For a uniform medium $\boldsymbol{\Omega}$ is constant and its modulus is

$$|\boldsymbol{\Omega}| = \frac{d\Delta \varphi}{dz} = \frac{\omega}{c} (n_1 - n_2)$$

Where $\Delta \varphi$ is the rotation angle on the sphere.
The evolution equation

In a toroidal plasma the vector $\Omega$ is defined by the magnetic field components

$$\Omega = \frac{\omega_p}{2c\omega^3} \begin{pmatrix} \left( \frac{e}{m_e c} \right)^2 (B_x^2 - B_y^2) \\ \left( \frac{e}{m_e c} \right)^2 (2B_x B_y) \\ 2\omega \frac{e}{m_e c} B_z \end{pmatrix}$$

In general $\Omega$ depends on $z$ and the evolution equation represents a sequence of infinitesimal rotations about an axis that moves on the Poincaré sphere

$$\frac{ds(z)}{dz} = \Omega(z) \times s(z)$$

$B_x$ toroidal field
$B_z$ poloidal field
The transition matrix (1)

The evolution equation can be written in matrix form

\[ \frac{ds(z)}{dz} = A(z) \cdot s(z) \]

whose formal solution is

\[ s(z) = M(z) \cdot s_0 \]

\( M \) is the transition matrix (the Mueller matrix of the plasma).

This equation describes two effects:

the change of \( \Psi \) (rotation of the axis of the polarization ellipse) --> Faraday Rotation
the change of \( \chi \) (change of ellipticity) --> Cotton-Mouton effect
The transition matrix (2)

In general \( \mathbf{M} \) is express by a series expansion. When the plasma effects are small only the first terms is significant:

\[
\mathbf{M} = \mathbf{I} + \mathbf{M}_1 + \mathbf{M}_2 + \ldots
\]

\[
\mathbf{M}_1 = \begin{pmatrix}
0 & -W_3 & W_2 \\
W_3 & 0 & -W_1 \\
-W_2 & W_1 & 0
\end{pmatrix}
\]

\[
W_1 = C_1 \int_{z_0}^{z_1} n_e(z) \left( B_x^2 - B_y^2 \right) dz
\]

The Faraday effect is described by \( W_3 \)

\[
W_2 = 2C_1 \int_{z_0}^{z_1} n_e(z) B_x B_y dz
\]

The Cotton-Mouton effect is described by \( W_1 \) and \( W_2 \)

\[
W_3 = C_3 \int_{z_0}^{z_1} n_e(z) B_z dz
\]

\[
C_1 = 2.42 \times 10^{-20} \, \lambda^3 m^2 T^{-2}
\]

\[
C_3 = 5.23 \times 10^{-19} \, \lambda^2 m^2 T^{-1}
\]

(\( \lambda \) in mm)
Polarimetry in a tokamak

In a tokamak measurement of Faraday rotation gives $W_3$ i.e line integrated $n_e B_\parallel$ \(\text{(poloidal field if } n_e \text{ is known)}\)

Measurement of Cotton-Mouton effect gives $W_1$ (and $W_2$) i.e line integrated $n_e B_\perp^2$ \(\text{(} n_e \text{ if } B_\perp \text{ is known)}\)

When the Cotton-Mouton effect is significant, this can give a measurement of $n_e$ alternative to interferometry
Schemes for polarimetry

The pure polarimeter: input polarization may be fixed (static polarimeter) or modulated.

The interferometer/polarimeter: The polarimetric measurement (usually static) is combined with that of an interferometer.
The static polarimeter: RFX

Major radius, R 2m
Minor radius, a 0.459m
Volume ~ 8.3m³
Plasma current 2MA
Maximum toroidal magnetic field $B_\phi$ 0.7T

Table 4.1: RFX parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Obtained value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Current</td>
<td>1.7 MA</td>
</tr>
<tr>
<td>Discharge duration</td>
<td>500ms</td>
</tr>
<tr>
<td>Electronic temperature</td>
<td>1.2keV</td>
</tr>
<tr>
<td>Electronic density</td>
<td>$2 \div 6 \cdot 10^{19}$ m⁻³</td>
</tr>
<tr>
<td>Electronic confinement time $\tau_E$</td>
<td>2ms</td>
</tr>
</tbody>
</table>

Table 4.2: Excellent performances obtained at RFX-mod

only Faraday rotation is significant in RFX
Principle of the measurement

layout of the RFX polarimeter

the 36 m FIR beamline (in N₂)

Laser specifications

- CO₂ pump laser 200W power
- CH₃OH FIR cavity λ = 118.8μm and 200mW CW chopped output power
- Chopper frequency 3kHz
- 31 m optical line in controlled Nitrogen atmosphere
Detector assembly

\[ S_1 + S_2 = S_{\text{sum}} \]
\[ S_1 - S_2 = S_{\text{diff}} = \sin 2\alpha = 2\alpha \]

Detection section

- 45° wire grid to divide the beam into two components
- Parabolic mirrors with focal length 100mm
- Pyroelectric detectors DLATGS-type with incorporated FET
- Preamplifier with a voltage gain of 100
- Responsivity 3V/W
- NEP $2 \times 10^{-8}$ W/Hz$^{1/2}$

Detector assembly diagram:

- Parabolic mirrors
- Polarizer
- Rotating half wave plate
- Laser radiation
- Detector

Machine Hall

Diagnostic Hall

Fig. 6: Block diagram of the signal processing equipment.
Examples of experimental data

Faraday rotation measurements have been obtained in high current (Ip > 1MA) pulses in large density range: Faraday rotation angles greater than 15° have been measured, wider than the simulation prediction. Analyses are in progress in early May 09.
Interferometer-polarimeter in TEXTOR

- Schematic drawing of the multichord FIR (HCN laser) interferometer / polarimeter on TEXTOR
- line-integrated $n_e$ and Faraday rotation angles measured along 9 vertical and 1 horizontal chords
Methods of polarization modulation

Static polarimeters are based on amplitude measurements (affected by noise and laser power fluctuations)

Polarization modulation of the probing beam transform the measurement in a phase measurement (laser power independent, highly reliable).

Modulation methods:

- Mechanical (rotating $\lambda/2$ or $\lambda/4$ waveplate) $\nu \leq 1$ kHz
- Photoelastic modulator (periodically strained crystal) $\nu \approx 50$ kHz
- Beam combination $\nu \approx 5$ MHz

One or two polarimetric parameter may be modulated to measure one or two polarimetric effects (Faraday rotation and Cotton-Mouton).
The rotating half-wave polarimeter on MTX

\[ S_{\text{pol}} = A \cos(4\omega_R t + 2\alpha) \]

Measurement on 15 chords
NSTX interferometer polarimeter

- Two FIR laser beams (linearly polarized) are combined and transformed into left- and right-hand circularly polarized probe beams with a small frequency difference ($\omega_1 - \omega_2 \sim 2$ MHz)
- Third laser is Stark-tuned: the gain curve is shifted by applying a transverse DC voltage to the cavity, and operates $\sim 5$ MHz away from the other two lasers.
The rotating quarterwave method (Segre U method)

Only one polarimetric parameter is changed with the previous methods so only Faraday rotation can be measured.

In the rotating quarterwave method (Segre U method) two polarimetric parameters are varied and also the Cotton-Mouton effect can be measured (with the same detector)

\[ S_{out} = P + Q_2 \cos(2\omega_0 t + \Phi_2) + Q_4 \sin(4\omega_0 t + \Phi_4) \]

\[ \tan \Phi_2 = W_3 + \frac{p}{q} W_1 \]

\[ \tan \Phi_4 = W_3 \]
The photoelastic modulator (MIR)

A crystal in which a standing strain wave intruduces periodical changes in the refraction index for the two perpendicular linear polarizations.

Frequency of modulation 50 kHz, available in the MIR (CO2), experimental device developed for 57 μm.

 Produces an alternating polarization modulation

\[ S_{out} = A(1 + s_2 \cos(\rho_0 \sin(\omega_0 t)) + s_3 \sin(\rho_0 \sin(\omega_0 t))) \]
The JET interferometer-polarimeter

**THE INTERFEROMETER/POLARIMETER DIAGNOSTIC AT JET**

Main features [2]:
- DCN laser at $\lambda=195\mu$m
- Reference beam modulated at 100 kHz
- 4 vertical and 4 lateral channels
- Very long optical path: 80m
- InSb He-cooled detectors
- Cotton Mouton effect is routinely measured on three channels [3]

![Diagram of the interferometer-polarimeter setup]

**Figure 1:** Polarimetry set-up

Signals:
- $i(t) = E_x^{(0)} \cos(\alpha t)$
- $p(t) = E_y^{(0)} \cos(\alpha t - \varphi)$

$R = \frac{PSD}{RMS} = C^{-1} \tan \Theta \cos \Phi$

$R' = \frac{PSP}{\sqrt{RMS \cdot RMP}} = C^{-1} \tan \Theta \sin \Phi$

![Polarization ellipse diagram]

**Figure 3:** Polarization ellipse. The relation between the two representation are:

- $\tan 2\psi = \tan 2\Theta \cos \Phi$
- $\sin 2\chi = \sin 2\Theta \sin \Phi$
Density measurements by Cotton-Mouton effect

3) Comparison between the line integrated density evaluated by interferometer (solid line) and by the real time polarimetric measurements (dotted line) for channel 2 (black), 3 (red) and 4 (magenta) of interferometer/polarimeter at JET (Figure 7)
• Control of the current density profile becomes a paramount issue for the modern tokamak experiments.

• Polarimetry can provide information on the **density** and **magnetic field** distribution inside plasma (current profile), utilizing the Faraday effect in a magnetized plasma.

• In order to evaluate $B_{\parallel}$ from the rotation angle, the electron density is necessary. This can be done by interferometry or using the **Cotton–Mouton** effect since the transverse field for a poloidal beam is the well known toroidal field $B_t$.

$$\alpha_{CM} = 2.46 \times 10^{-11} \lambda^3 \int n_e B_t^2 \, dz$$

Both $n_e$ & $B_{\parallel}$ must be measured along same chord simultaneously.
Expected effects for $\lambda = 57 \, \mu m$

Calculated Faraday rotation angles (double pass through the plasma) for a horizontal fan of chords (right top) and the corresponding ellipticity values (right center); with q-profile, pressure profile and electron density profile on the left.

Very small ellipticity (Cotton-Mouton effect)
Two general approaches exist to evaluate plasma current profile

### Polarimeter - polarimeter

- \( B_{||} \) polarimeter (Faraday)
- \( n_e \) polarimeter (Cotton–Mouton)

### Polarimeter - interferometer

- \( B_{||} \) polarimeter (Faraday)
- \( n_e \) interferometer

#### Advantages

- There are no fringe jumps in principle
- Lots of application on major tokamaks (JT-60U, JET, TotaSupra, RTP, NSTX, MST…)

#### Drawbacks

- Complicated channeling and calibration due to coupling of Faraday rotation and Cotton-Mouton effect.
- Despite promising theoretical and numerical results there is very limited experimental support. 1ch pure Cotton–Mouton polarimeter (W7-AS)
- Fringe jumps
- Mechanical vibrations
- Small Faraday rotation in the core plasma region

**Shorter wavelength laser, with smaller refraction and two color interferometer solve the problems**
The tangential interferometer-polarimeter for ITER

5 chords for "real-time" measurement to be used in $n_e$ feedback control

TIP gives "double" density measurements:

$$\Phi = 2.82 \times 10^{-15} \lambda \int n_e(z) dz$$

$$\Psi_F = 2.62 \times 10^{-13} \lambda^2 \int n_e(z) B_{//}(z) dz$$

Magnetic field known along tangential chords

- Double-pass system utilizing retro-reflectors
- Retro-reflectors mounted in recessed plugs in shield wall
- Optical labyrinth through shield wall
**Faraday Rotation and Interferometer Phase Shifts**

<table>
<thead>
<tr>
<th>Two $\lambda$ considered:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MIR 10.6/5.3 $\mu$m</strong> &amp; <strong>FIR 57/47 $\mu$m</strong></td>
</tr>
</tbody>
</table>

Density profiles approximated by:

$\rho_e = d \times 10^{20} \left( 1 - \left( \frac{r}{a_o} \right)^b \right) \, m^{-3}$

**Low-Density: Steady State**  
$d=1, b=10, \rho_e = 1 \times 10^{20} \, m^{-3}$

**High-Density: Gas Injection, Pellets, etc.**  
$d=10, b=2, \rho_e = 1 \times 10^{21} \, m^{-3}$

- Faraday rotation $< 2\pi$ for 10.6 $\mu$m  
  but $> 2\pi$ for 57 / 47 $\mu$m  
  Polarimetry phase shift has potential for fringe skips at 57 / 47 $\mu$m.
- Interferometry phase shifts large ($10^2$-$10^3$ fringes) at all $\lambda$‘s
- At 10.6 $\mu$m only for $\rho_e > 10^{22} \, m^{-3}$, Faraday phase shifts $>2\pi$ and refraction may be large

- $B_T = 5.3 \, T$  
  $a_o = 2 \, m$  
  $R_o = 6.2 \, m$

Density profiles approximated by:

- Low-Density: Steady State
- High-Density: Gas Injection, Pellets, etc.
Two-color interferometry

Two-color interferometer resolution given by:

\[ \delta \phi = \text{Phase Measurement Error} \]
\[ \lambda = \text{Wavelength} \]

\[ \delta n_e L \propto \frac{\delta \phi}{(\lambda_1 - \lambda_2)} \]

<table>
<thead>
<tr>
<th>( \lambda_1 ) (( \mu \text{m} ))</th>
<th>( \lambda_2 ) (( \mu \text{m} ))</th>
<th>Error (degree)</th>
<th>Path Length (m)</th>
<th>Required Resolution ( nL ) (m(^{-2} ))</th>
<th>Form ula Required Resolution ( nL ) (m(^{-2} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.59</td>
<td>5.3</td>
<td>1</td>
<td>20</td>
<td>2.0E+19</td>
<td>2.0E+17</td>
</tr>
<tr>
<td>10.59</td>
<td>9.27</td>
<td>1</td>
<td>20</td>
<td>2.0E+19</td>
<td>2.0E+17</td>
</tr>
<tr>
<td>12.1</td>
<td>9</td>
<td>1</td>
<td>20</td>
<td>2.0E+19</td>
<td>2.0E+17</td>
</tr>
<tr>
<td>57.2</td>
<td>47.6</td>
<td>1</td>
<td>20</td>
<td>2.0E+19</td>
<td>2.0E+17</td>
</tr>
</tbody>
</table>

At lowest specified density of \( n_e = 1 \times 10^{18} \text{ m}^{-3} \), no wavelength fulfills 1% line-density requirement, even for central chord.
10.59 μm polarimetry meets requirements in $n_e \sim 10^{19} \text{ m}^{-3}$ range with 1 kHz bandwidth
- over all ranges, 10.59 μm phase shift is $< 2\pi$ = no fringe jumps
- can be used to correct 2-Color Interferometer for fringe errors

Assuming 0.1 degree resolution, 47/57 μm polarimetry meets requirements even at minimum density, BUT
- even at moderate densities $\sim 10^{20} \text{ m}^{-3}$, fringe jumps are possible
Refraction negligible at 10.6 μm

- Density profile refraction effects at 10.6 μm are negligible
- For high-density case (10^{21} m^{-3}) displacements several cm at 57/47 μm
- Radial displacement doubled by retro-reflector
- Path length change introduces negligible line-density errors at all λs
- Refraction likely dominated by ELMs, pellets, and H-mode pedestals - 3D calculations to be carried out
Control of plasma facing mirror degradation

Plasma facing mirrors in ITER will be subject to a variety of deleterious effects - a concern for first mirrors and retro-reflectors

Problems Include:
- Erosion due to charge exchange neutrals
- Impurity deposition
- Both affect reflectivity and polarization dependence

Mitigate deleterious effects by:
1. Reducing Solid Angle ($d\Omega$)
2. Temperature Control
3. Choice of Material

44 cm recess $\Rightarrow$ ~ 1/340 reduction in $d\Omega$

5 $\mu$m Erosion* is Reduced to 15 nm = Acceptable

*V.S. Voitsenya et.al., RSI, 76, 083502 (2005)
Laser Beam Diameter < 3.5 cm at 10.59 μm

- Gaussian beam propagation using ZEMAX
- Beam diameter ~ $\lambda^{1/2}$
- Area of hole in wall, solid angle, and mirror erosion ~5x larger for 57 μm
- Longer $\lambda$ does not help mirror erosion problem
Finite Temperature Effects

- Finite $T_e$ will cause apparent reduced density using cold plasma interpretation
- At 15 keV effect is 4.4% for Interf. and 6% for Polarimetry

Analytic Approx. by Mirnov:

Interfer.  \[ \phi = c_I \int n_e dl - \frac{3}{2} \frac{c_I}{m_e c^2} \int n_e T_e dl \]

Faraday \[ \alpha = c_F \int n_e B_{\parallel} dl - \frac{2c_F}{m_e c^2} \int n_e T_e B_{\parallel} dl \]

Summary TIP for ITER

- CO₂ laser 10.6/5.3 μm based TIP meets ITER requirements
  - Provides 2 independent density measurements (no fringe skips)
  - well-developed technology
  - negligible refractive effects
- First mirror survivability issues can be resolved
  - solid angle reduction
  - temperature control
  - Longer wavelengths require larger solid angles -> little advantage
- Use multiple separate first mirrors and a common first wall penetration to maximize redundancy and minimize exposure
- Feedback alignment system required for each chord
- Thermal effects can contribute 5-10% error unless properly treated