Advanced Laser Diagnostics for Electron Density Measurements

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- Introduction
- Cotton-Mouton polarimeter on CHS
- Two color laser interferometer

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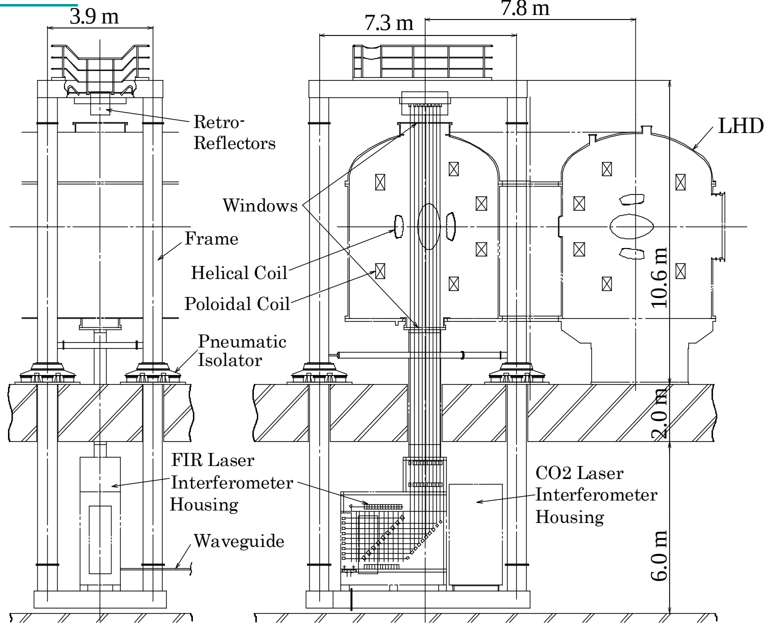
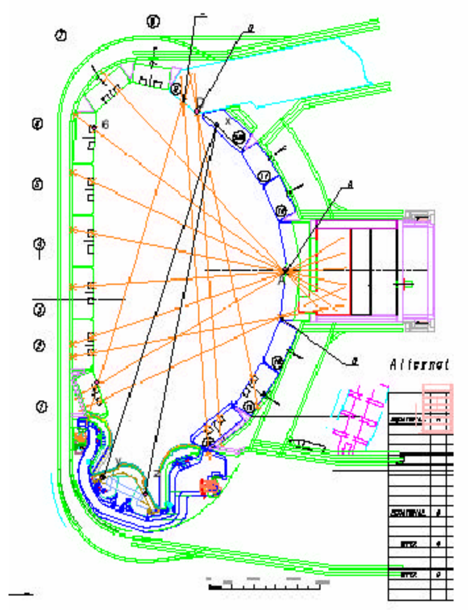
Optimization of probe beam wavelength

FIR Laser Interferometer installed on the LHD



Proposed Polarimeter system for ITER



Need of a short wavelength laser

λ:~ 50 μm

➢**On LHD, a 13-channel 119-μm CH_3OH far infrared laser interferometer has been routinely operated for the precise measurements of the electron density profile .**

➢**The maximum densities of over 4 x 10^{20} m^{-3} were achieved by using pellet fueling and LID pumping.**

➢**A poloidal polarimeter system has been designed for the measurements of current density profile in ITER.**

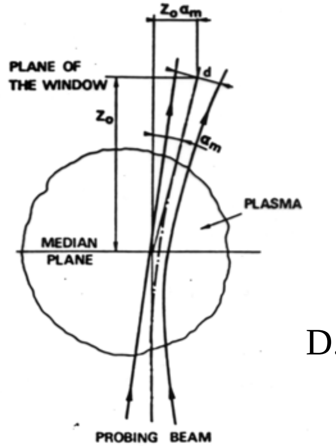
➢**Proposed laser oscillation line is 119-μm CH_3OH, bu the beam bending effect due to plasma density gradien is large.**

➢**Laser oscillation lines around 50μm are considered to be suitable from the consideration of the beam refraction and signal-to-noise ratio.**

Choice of probe beam wavelength

- The optimum wavelength suitable for interferometry/palarimetry can be selected from the following considerations

$$d = 2\left(\frac{\lambda Z_o}{\pi}\right)^{1/2} \rightarrow Z_o \alpha_m \le 2\left(\frac{\lambda Z_o}{\pi}\right)^{1/2}$$



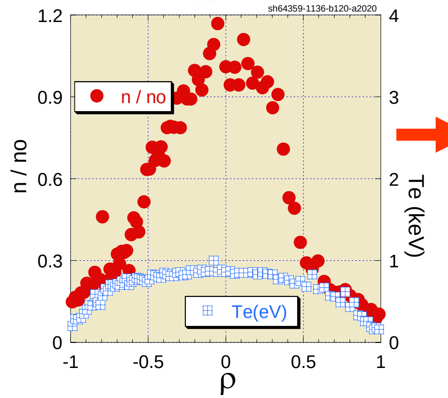
D. Veron

- ➢ Phase shift: $\varphi = 2.82\times10^{-15}\lambda\int_{z_2}^{z_1} n(z)dz$
- ➢ Cutoff frequency: $n_c = 1.11\times10^{15}/\lambda_0^2$ (m^{-3})
- ➢ Beam bending effect:

$$\alpha_m = \sin^{-1}\left(\frac{n_o}{n_c}\right) \cong \frac{n_o}{n_c} = 8.97\times10^{-16} n_o \lambda^2$$

$$\lambda \le 1.16\times10^{10}(Z_o n_o^2)^{-1/3} m$$

(Example: Zo = 3.8 m, $n_e(0) = 1\times10^{20}/m^3$ leads to $\lambda < 330\ \mu m$)



~50μm

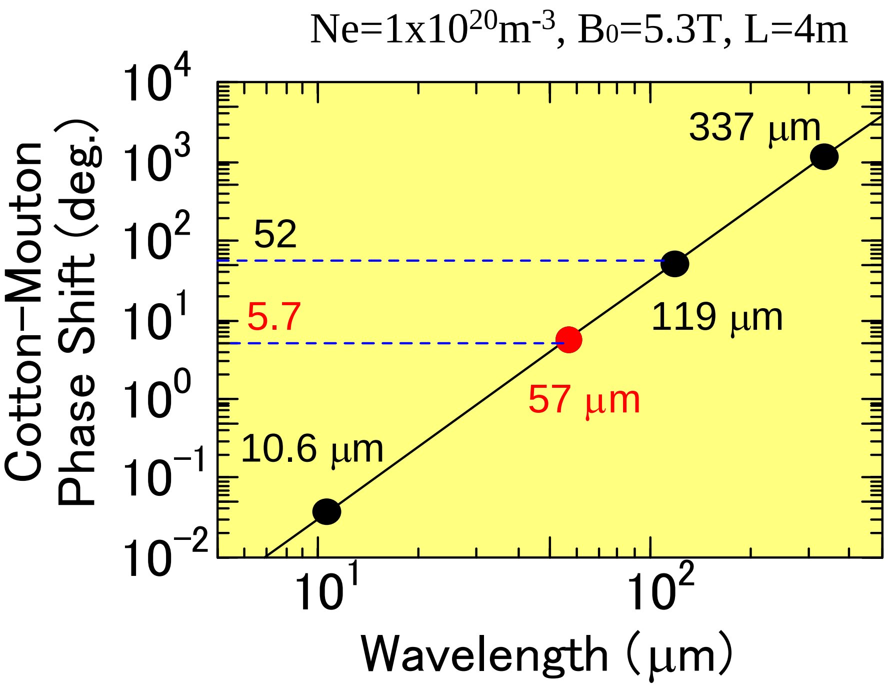
- ➢ Mechanical vibration: $\Delta\phi = 2\pi\Delta L\lambda^{-1}$
- ➢ Faraday rotation: k || B $\Omega = 2.62\times10^{-13}\lambda^2\int_{z_1}^{z_2} nB_{\parallel}dz$
- ➢ Cotton-Mouton effect: $\varepsilon = 2.45\times10^{-11}\lambda^3 B^2 n_e \Delta z$

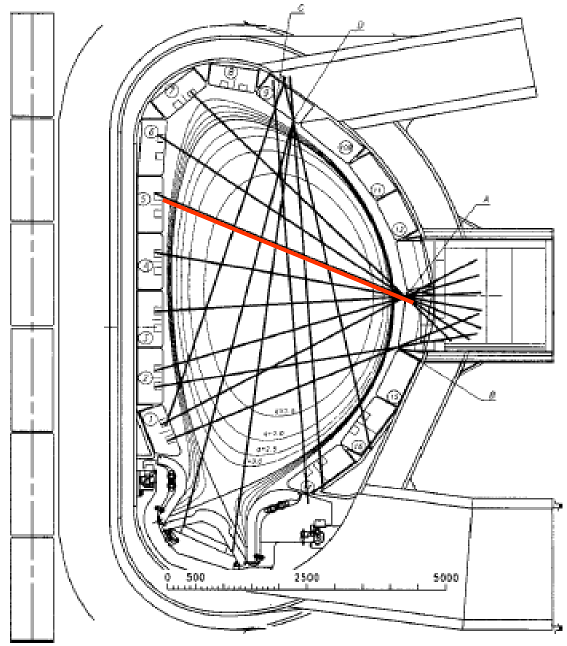
  k ⊥ B

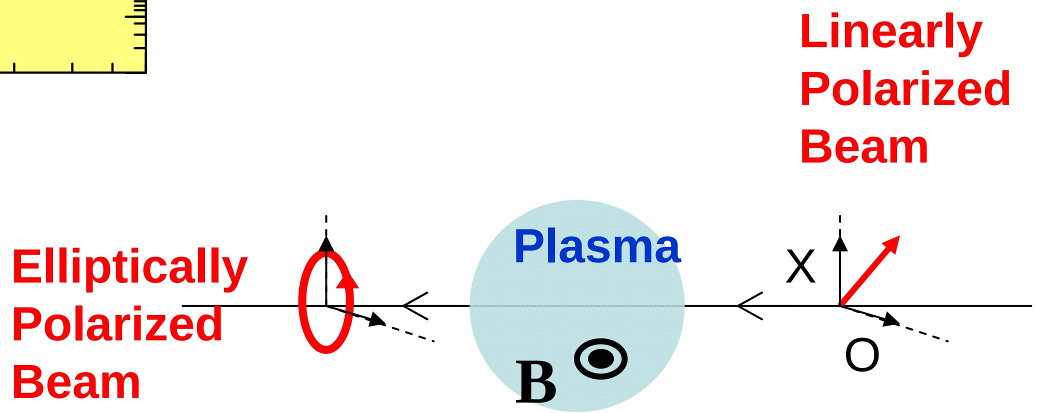
$n(0) = 4.2\times10^{20} m^{-3}$
T(0) = 0.87 keV
β(0) = 4.2 %
at B = 2.64 T

Selection of Wavelength for ITER Diagnostics

Dependence of phase difference by CM effect on wavelength of laser



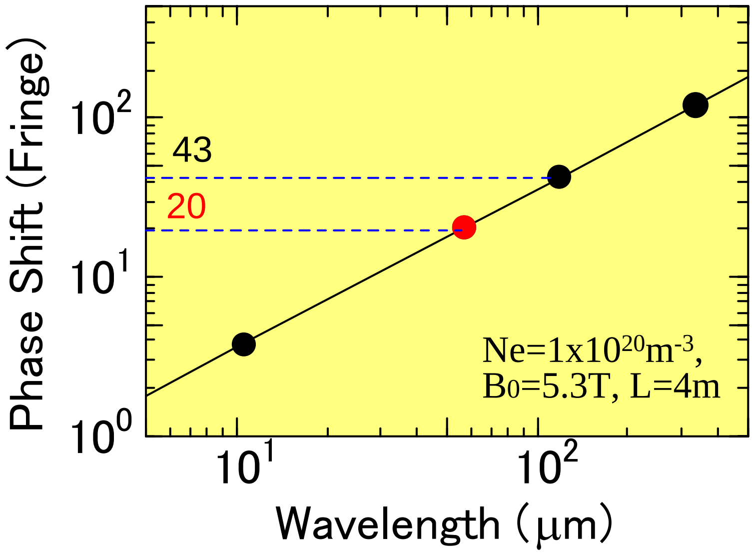


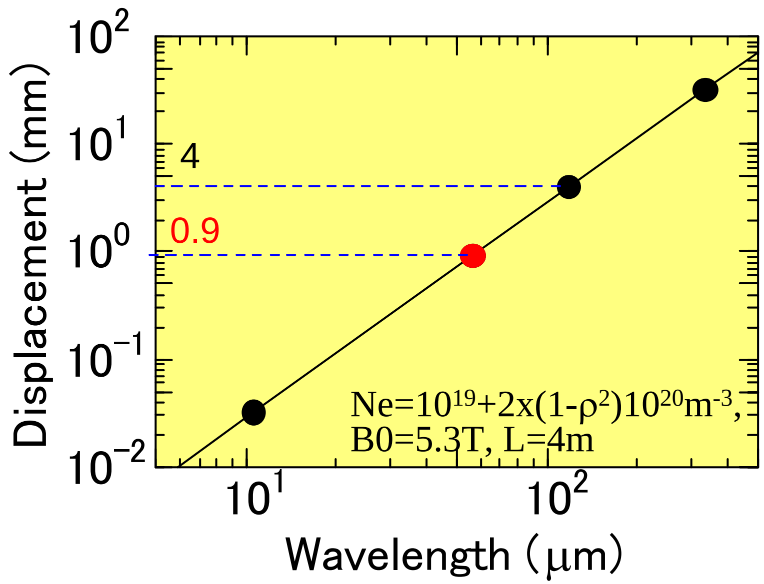


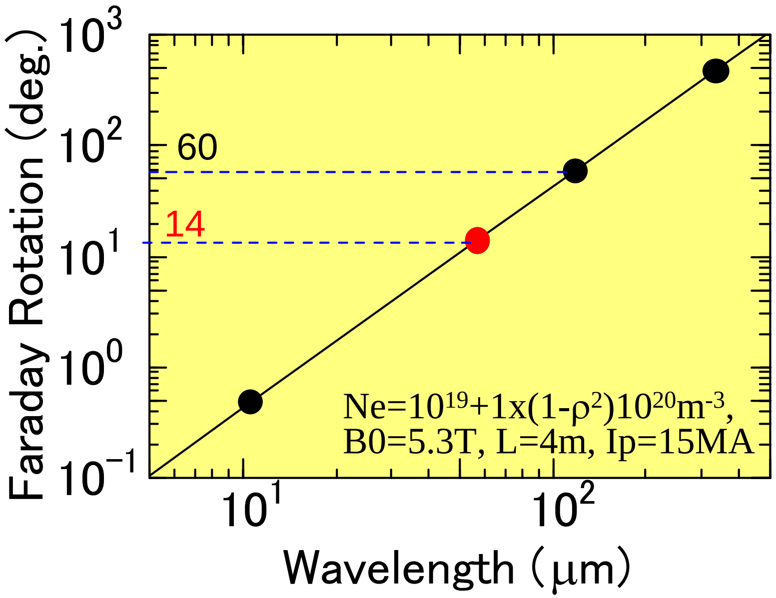
$$\phi_{\mathrm{CM}}\,[\mathrm{rad.}] = \phi_{\mathrm{O}} - \phi_{\mathrm{X}}$$

$$= 2.4\times10^{-20}\,\lambda[\mathrm{mm}]^3 \int n_e[\mathrm{m}^{-3}]\, B_\perp[\mathrm{T}]^2\, dl[\mathrm{m}]$$

Selection of Wavelength (continue)



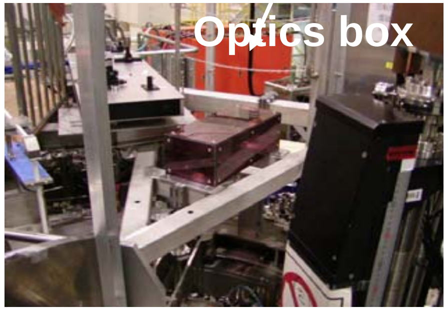


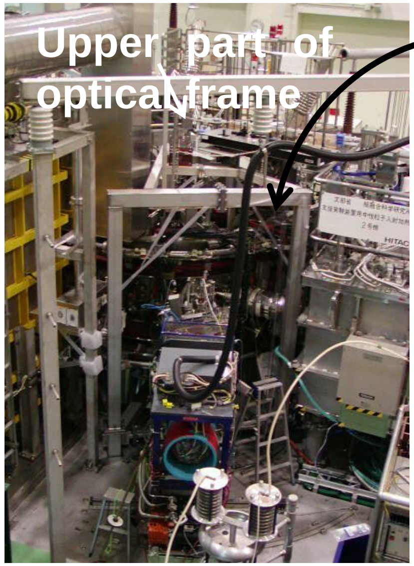


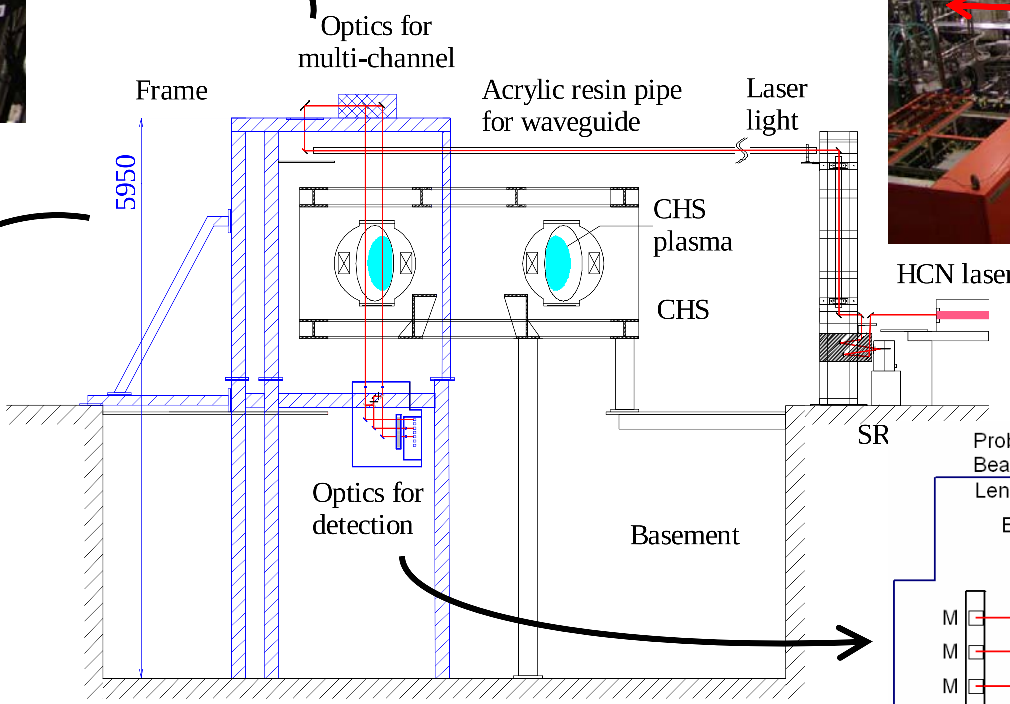
	57 μm	119 μm	Measurement
Phase	20 fringes	43 fringes	$\lambda \int n_e \, dl$
Rotation	14 deg.	60 deg.	$\lambda^2 \int n_e \, B \, dl$
Cotton−Mouton	5.7 deg.	52 deg.	$\lambda^3 \int n_e \, B_\perp{}^2 \, dl$
Displacement	0.9 mm	4 mm	$\lambda^2 n_0$

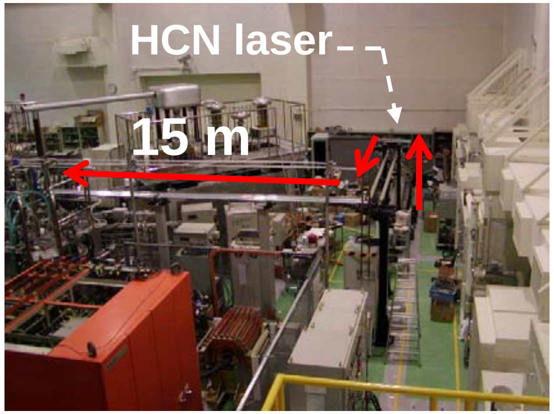
Cotton-Mouton Polarimeter for Electron Density Measurement with HCN laser on CHS

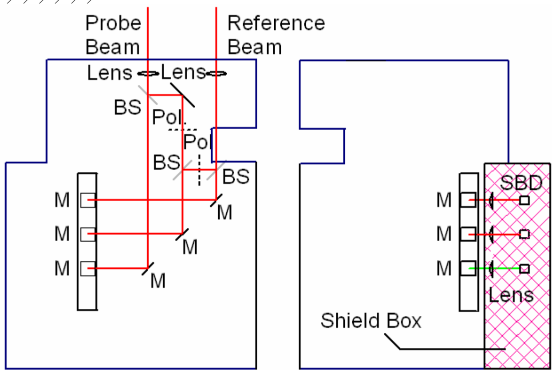
$$\varepsilon = 2.45\times10^{-11}\lambda^3 B^2 n_e \Delta z$$





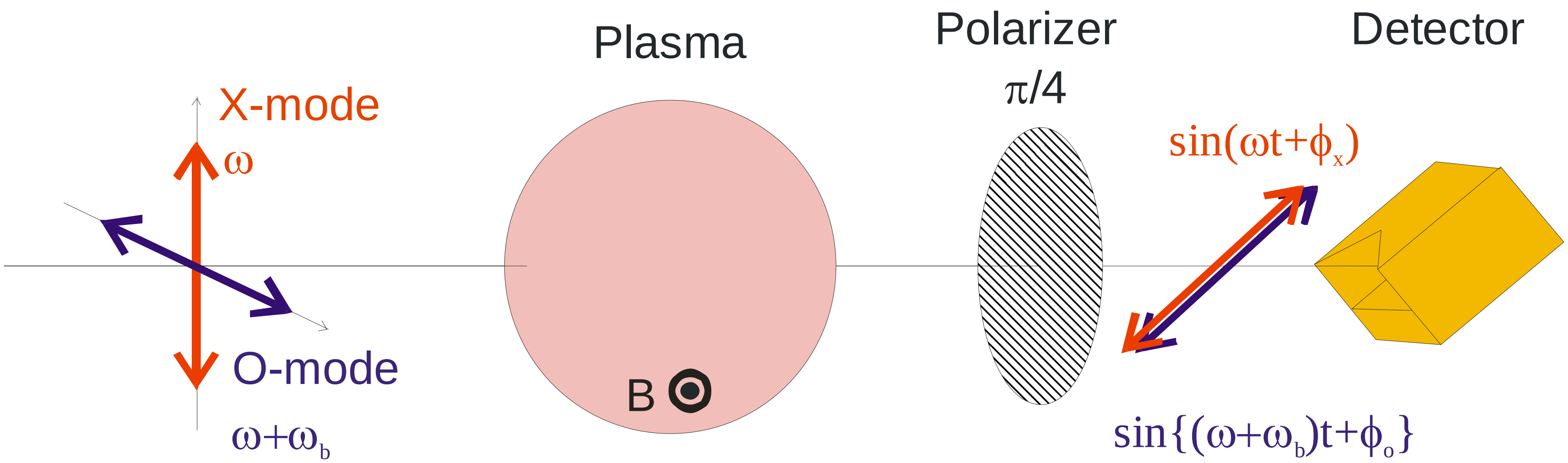






- Path length from the laser to optical frame is about 15 m.
- Dielectric waveguide (ϕ 47 ID) made of acrylic resin is used to transmit laser beams. The transmission efficiency is totally about 80%.
- Detectors are schottky barrier diodes.

Measurement Method of CM effect



Probe signal:

$$I_{probe} = \left[\sin\{(\omega+\omega_b)t+\phi_O\}+\sin(\omega t+\phi_X)\right]^2$$

$$\propto \cos\{\omega_b t + (\phi_O - \phi_X)\} + \text{Const.}$$

$$= \phi_{CM}$$

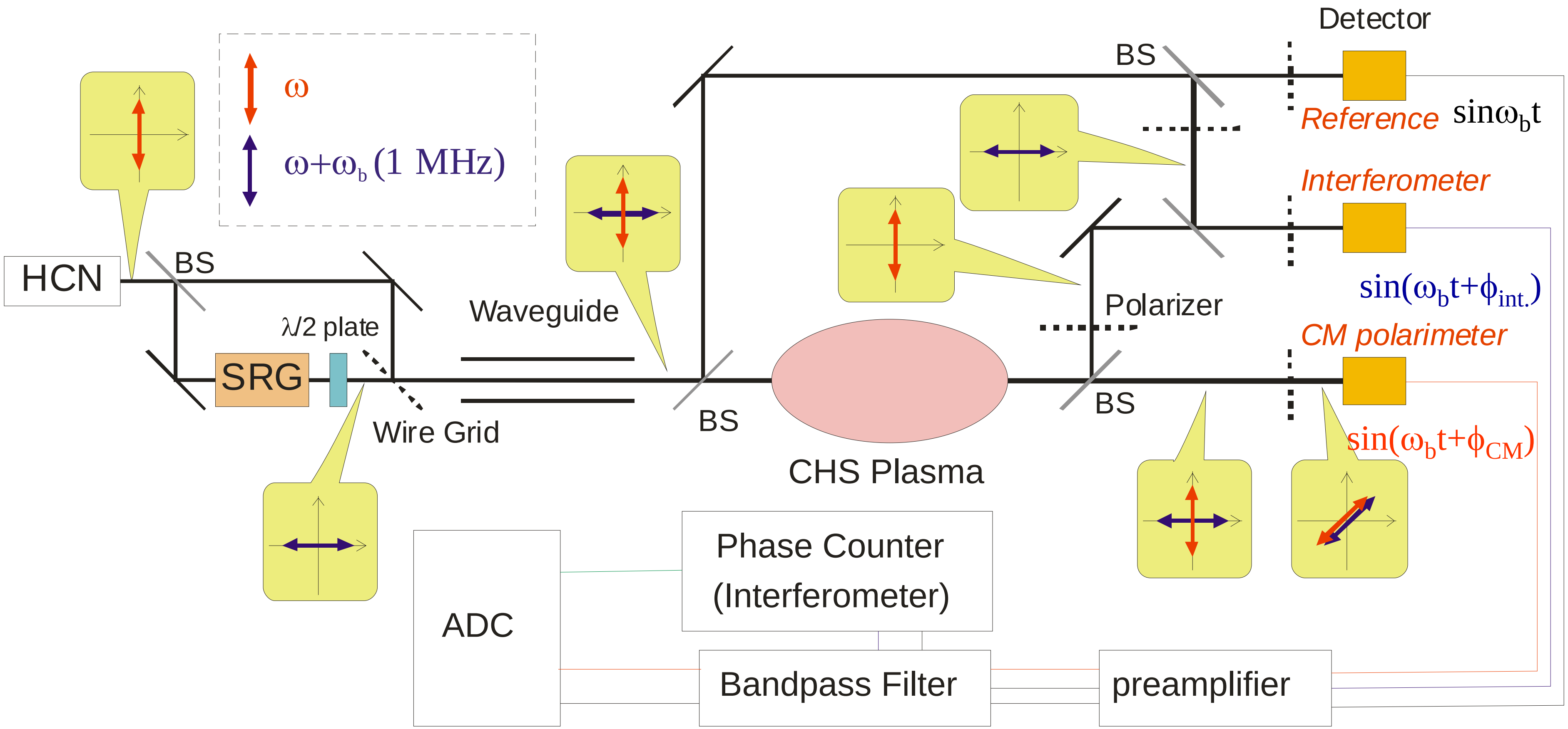
Reference signal: $I_{ref} \propto \cos(\omega_b t) + \text{Const.}$

S.E. Segre, Phys. Plasma 2 2908 (1995)

Phase difference due to Cotton-Mouton effect can be measured as a phase difference between probe and reference signal.

Free from amplitude variations due to oscillation instabilities of laser and beam deviation.

Optical Setup of CM Polarimeter with Int.

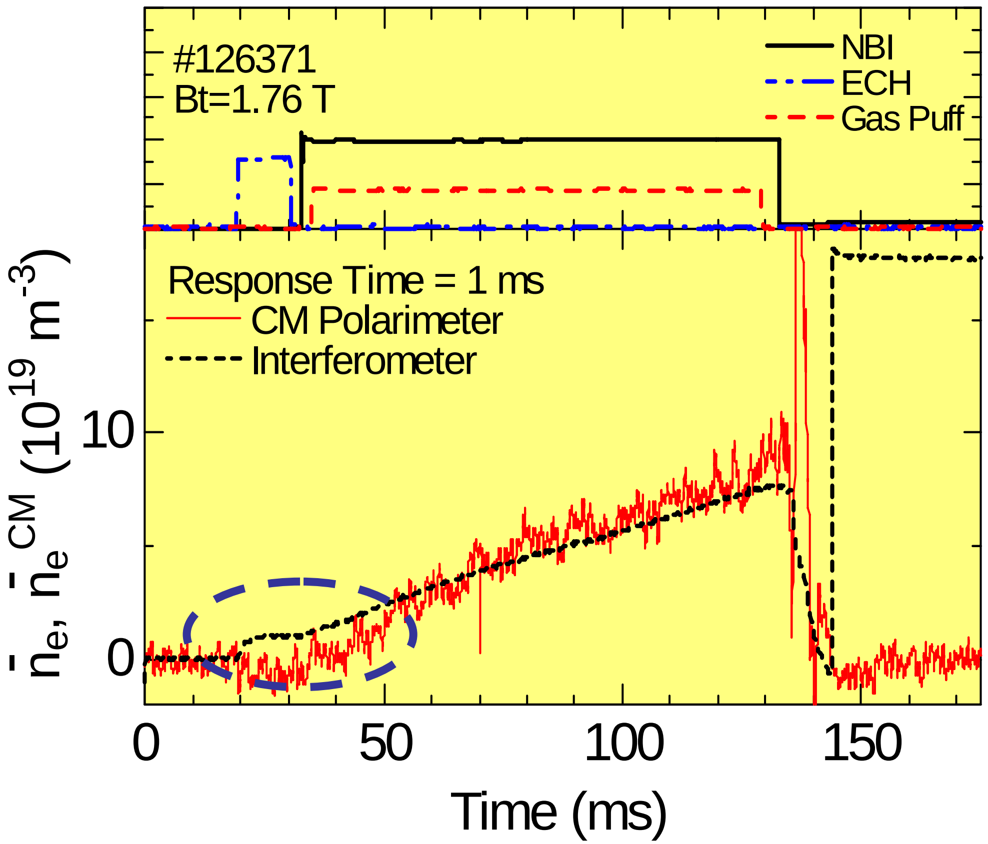


- Beat signal of 1 MHz
- Simultaneous measurement system of an interferometer and a CM polarimeter with the same plasma center chord in order to check the absolute value of CM phase difference.

This is almost same as the system proposed on W7-X.

Measurement Results

After improvement of cross and back talks



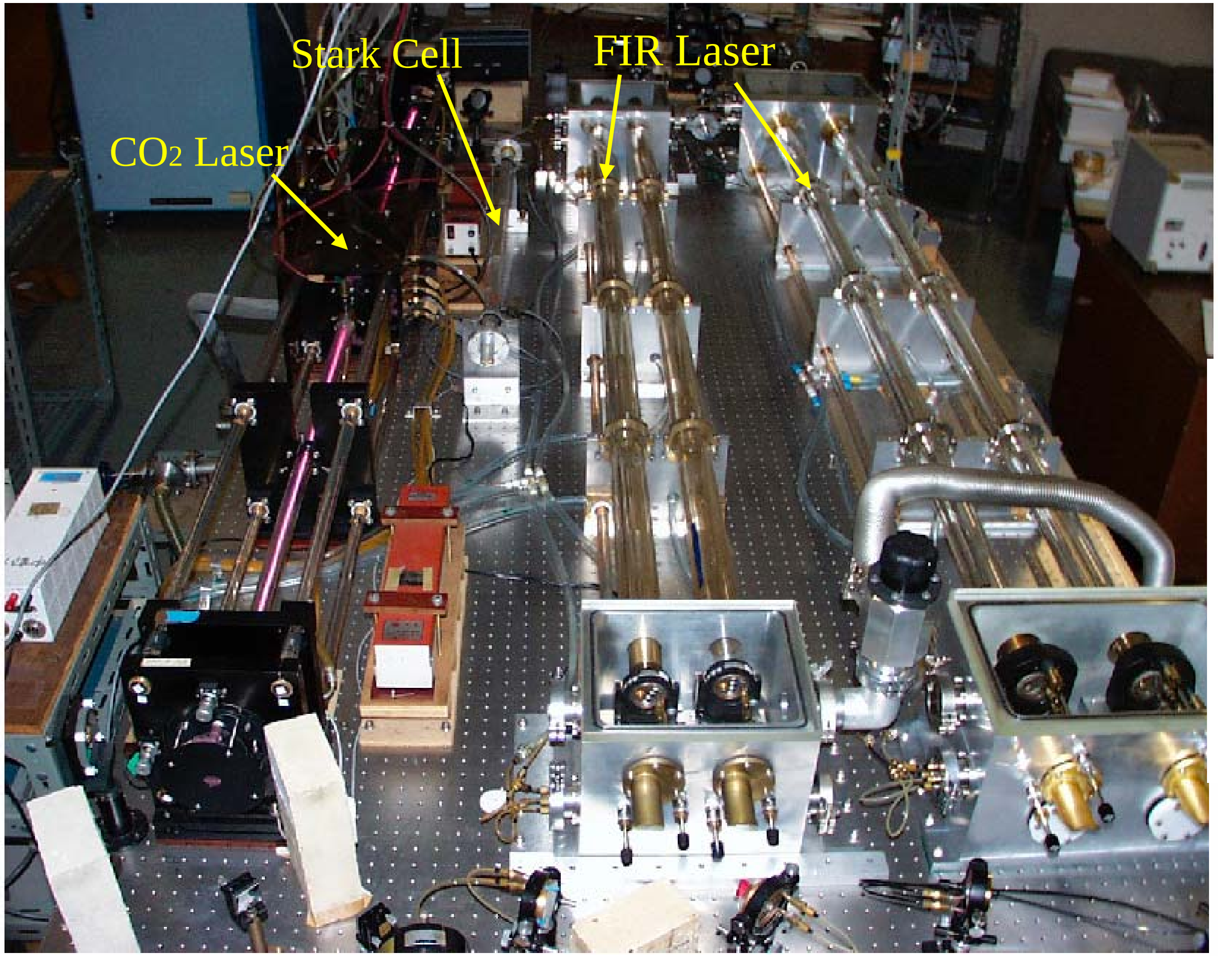
Phase difference due to Cotton-Mouton effect can be measured successfully.

The result of the polarimeter is almost consistent with that of the interferometer except initial phase of the discharge.
Amplitude of phase variations is within ±0.5 deg. with time constant of 1.0 ms.
Interferometer shows fringe jump errors twice (t=135,144ms)

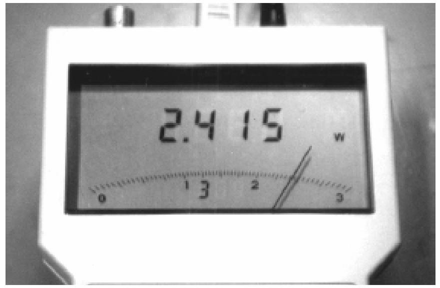
Cf. $\delta\phi_{CM} = 1\text{deg.with}\Delta t = 10ms$
JET CM Measurement

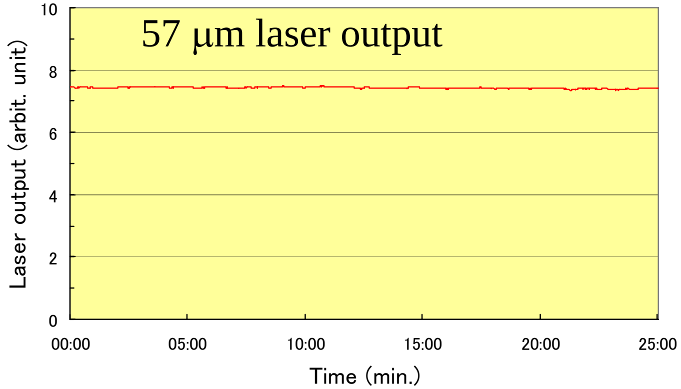
Development of a new two color FIR laser diagnostics

cw FIR laser system



The Highest Output Power





cwFIR laser		cwCO$_2$ laser	
Power [W]		Line	9R(8)
Total	2.4	Power [W]	138
57.2-μm	(1.6)	Flow rate [l/min]	
47.7-μm	(0.8)	CO_2+N_2 (33%:67%)	1.9
Pressure [Pa]		He	7.1
Total	60	Pressure [hPa]	37.2
CH_3OD	44	Current [mA]	55
He	16	Water temperature [℃]	22
Laser wall temperature [℃]	-6.4		

CO2 laser

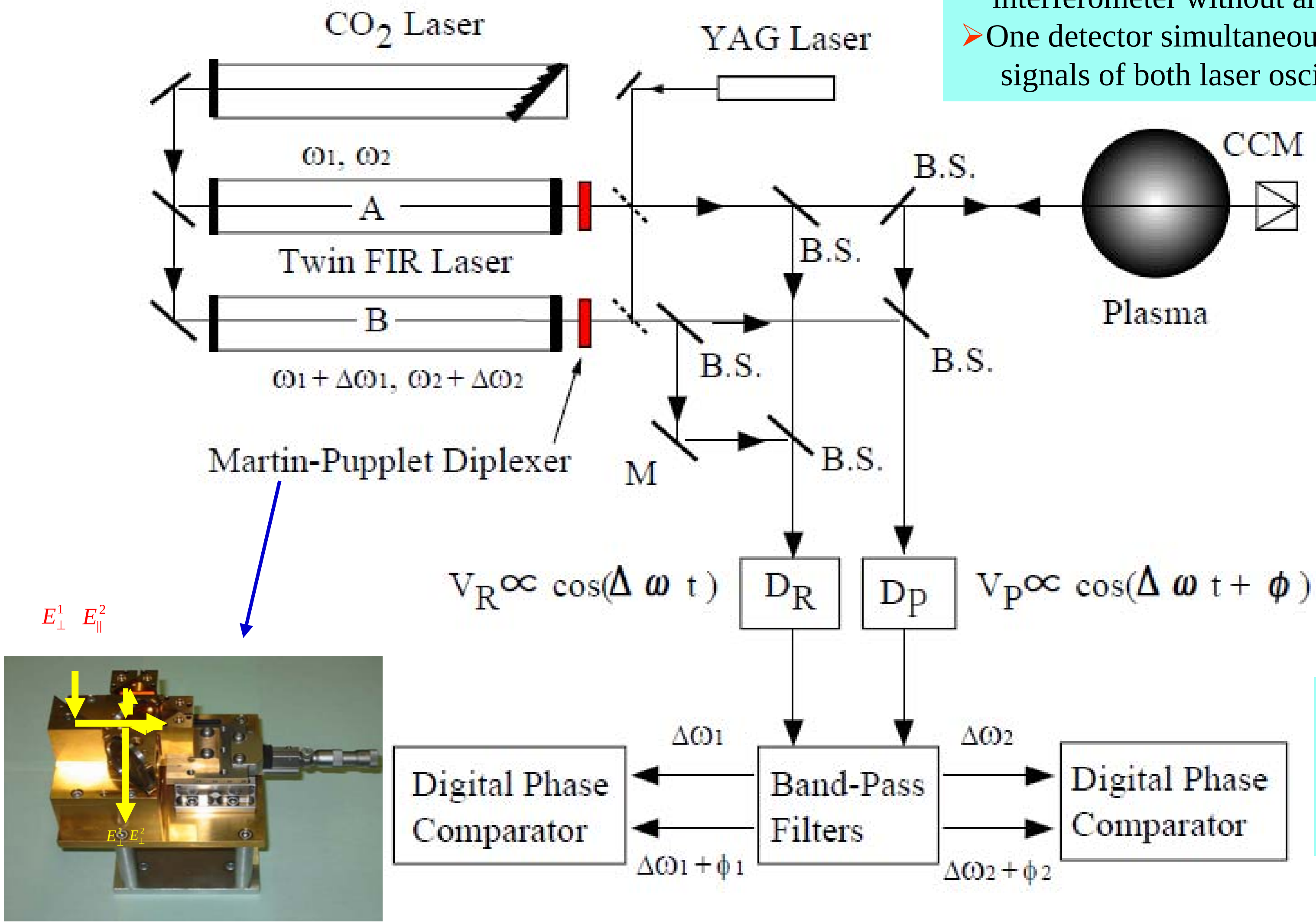
Cavity length: 3 m
Discharge length: 1.25 x2
Output coupler: ZnSe, 20 m radius curvature
Grating: 150 g/mm, blazed at 10.6 μm

FIR Laser

Cavity length: 2.9 m
Laser tube: 25 mm inner diameter
Input coupler: gold-coated copper M.
Output coupler: Silicon hybrid coupler

Two color FIR laser Interferometer

- 57.2 μm is optimum value to avoid refractive effects in high density operation of LHD and future fusion devices.
- Both laser beams pass the same optical path in the interferometer without any optical path difference.
- One detector simultaneously detects the beat signals of both laser oscillation lines.

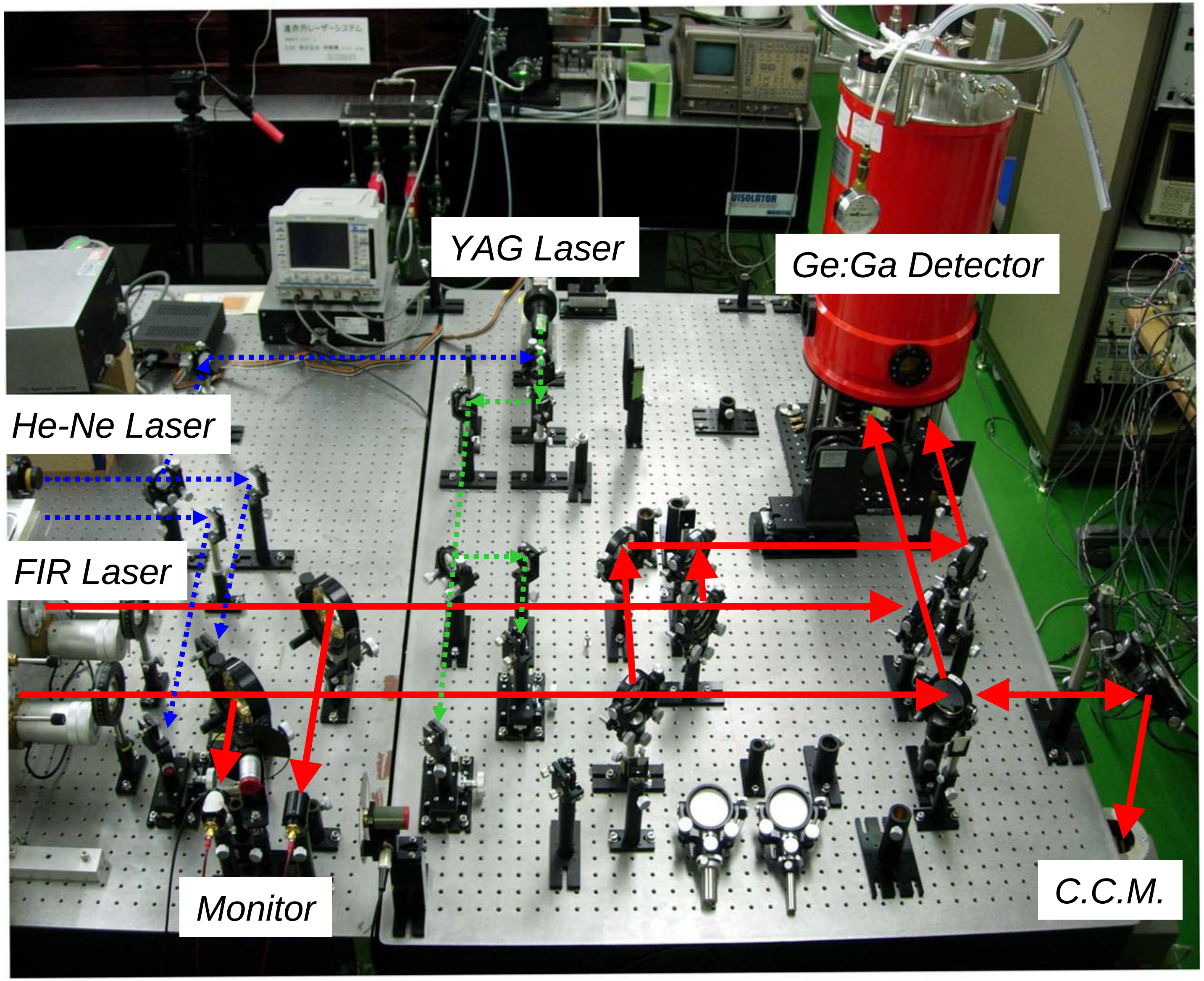


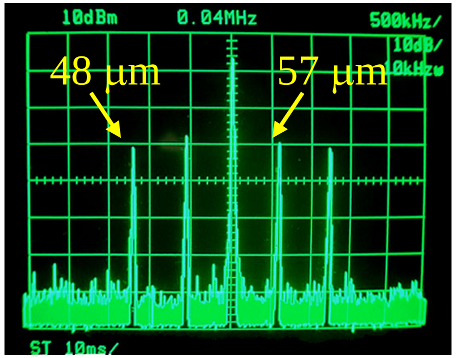
$E_\perp^1$ $E_\parallel^2$

$$\Delta\phi = \frac{\pi}{\lambda n_c}\int_{z_1}^{z_2} n_e(z)dz$$

$$= 2.82\times10^{-15}\lambda\int_{z_1}^{z_2} n_e(z)dz$$

Detection of two-color beat signals





10 dBm, 500 kHz/div

Two color beat signals detected by Ge:Ga photoconductor.

Beat frequency;

0.6 MHz for 57 μm

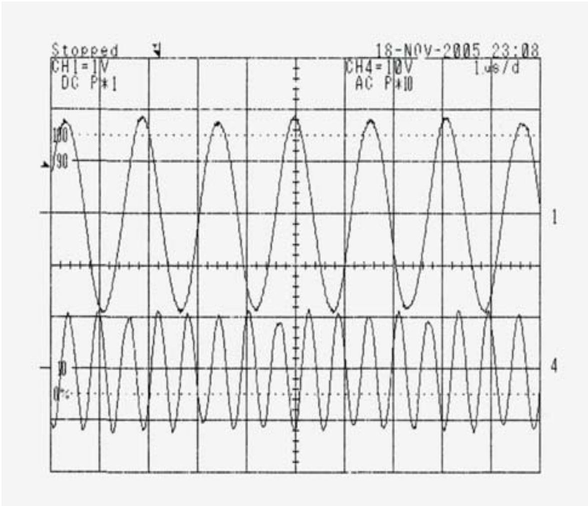
1.2 MHz for 48 μm

The frequency of the beat signals can be changed with the cavity length and pressure of the FIR laser.

Demonstration of Two color FIR laser Interferometer

57 μm
beat signal

48 μm
beat signal

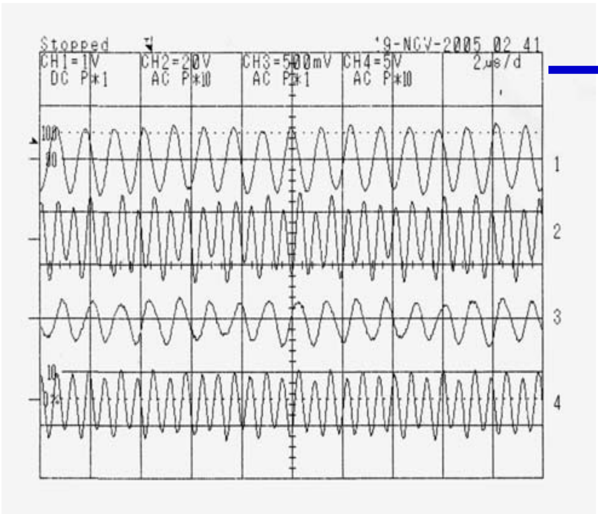


Detector (I)

57 μm
beat signal
48 μm
beat signal

Detector (II)

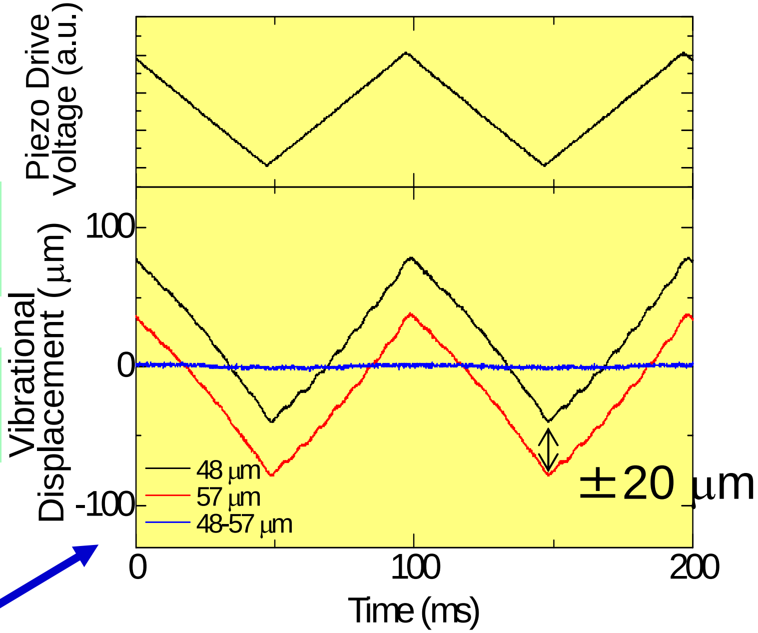
57 μm
beat signal
48 μm
beat signal



48-μm Laser Interferometer

57-μm Laser Interferometer

Phase Counter



Optical path length was modulated by using a piezo-electric transducer.

One detector simultaneously detects the beat signals of both oscillation lines, and each interference signal can be separated electrically – the 57.2 μm at 0.6 MHz and the 47.6 μm at 1.6 MHz.

Two color FIR laser interferometer work was successful in demonstration of mechanical vibration compensation.

SUMMARY

(1) A Cotton-Mouton polarimeter has been developed on CHS, combining with an interferometer.

(2) The measurement results of the polarimeter show a good agreement with the interferometer.

(3) A two color FIR laser interferometer is under development for high density plasmas on LHD. Simultaneous operation at 57.2μm and 47.7μm is confirmed.

(4) Two color beat signals are simultaneously detected by using a Ge:Ga photoconductive detector.

(5) Two color FIR laser work was successful in demonstration of mechanical vibration compensation.