# Optical design of modular multichannel Dispersion Interferometer for electronic density measurements in W7-X stellarator.

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A multichannel modular $CO_2$ Dispersion Interferometer (DI) has been designed by Zemax simulations to measure electron density profiles in W7-X stellarator. Basis of the design are Dispersion Interferometer Modules installed on TEXTOR tokamak [1] and being currently under test [2]. The principal determinants of this design are the size and shape of the multichannel transmission bench near the W7-X vessel and the positions of the lines-of-sight [3] as they are defined by the restrictions given by port apertures and the locations and aperture of the corner cube retroreflectors (CCR) integrated in the heatshield of W7-X. The optical design software provides the Gaussian characteristics of the probe beams, an optimal design of optical elements and the proper position of the waist of the beams on the CCR. For redundancy the optical system of these interferometer is designed in such a way that, in case of a single module failure, whatever line-of-sight can be illuminated from whatever interferometric module replacing the last mirror of a module which focuses the probe beams on the CCRs and using an auxiliary optical stage to steer the probe beams to the direction of required line-of-sight. This provides a high flexibility to the diagnostic since it would be possible to retrieve lines-of-sight of interest even in case of module failure with minimum impact in machine operation.

## I. INTRODUCTION.

Interferometry is a fundamental diagnostic in fusion devices that allows to measure the electron density profiles with high spatial and temporal resolutions by means of a phase shift measurement along several lines-of-sight. The main disadvantage of the interferometric techniques is the influence of mechanical vibrations that introduces errors in the phase measurements due to the plasma. The dispersive interferometers are an alternative method regarding with the two-color heterodyne interferometers [1]. Since a unique laser source is used, the setups are compact optical systems because a reference arm is not necessary and mechanical vibrations are compensated intrinsically. A modular multichannel dispersive interferometer is installed in TEXTOR tokamak (FZJ) and will be composed by ten single module dispersion interferometers (SIMDI) placed in a rack located under the fusion device but currently only four modules have been operating since 2010 [2]. For compactness each module (1600×320mm$^2$) is divided in two levels. Basically, the laser level module has a $CO_2$ and a He:Ne laser (to measure and to align respectively) and a Ge-lens telescope. The optical level is composed by a set of spherical mirrors, a frequency doubling crystal (FDC), an electrooptical cell (EOC) and a photodetector. These optical systems allow to control totally the propagation of the beams through the plasma and to focus them on the FDC and EOC in order to generate the second-harmonic beam and to modulate the fundamental beam at 250 KHz respectively. The goal of this work is to adapt these interferometric modules for W7-X stellarator taking into account its boundary conditions by Zemax simulations.

## II. REQUERIMETS FOR THE OPTICAL DESIGN OF MODULAR MULTICHANNEL DISPERSIVE INTERFEROMETER FOR W7-X.

The proposed optical design of the multichannel dispersive interferometer for W7-X stellarator is conditioned by the size of the modules (3200×320-500 mm$^2$), the plasma access windows (80 mm diameter), the vertical transmission bench (TB) of great dimensions, the positions of the lines-of-sight [3] and the sizes of corner cube retroreflector apertures (~26 mm) [4]. Figure 1 shows the size of transmission bench, the positions of SIMDIS and the lines-of-sight into the plasma.

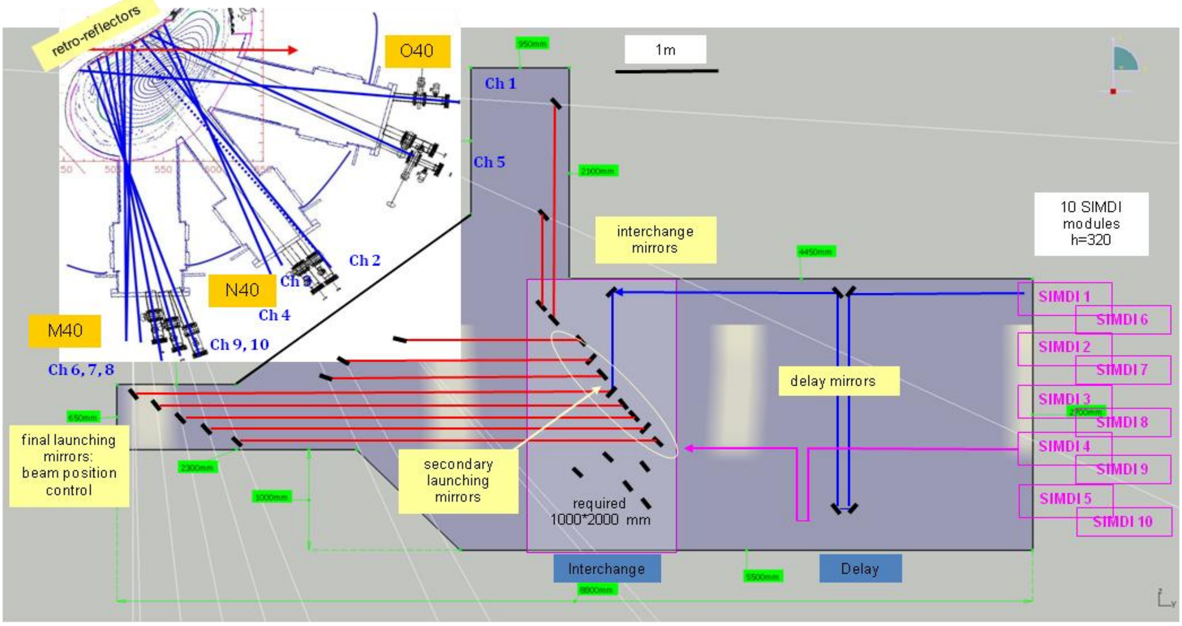


Figure1: Layout of the transmission bench, positions of SIMDIs and lines-of-sight for W7-X.

The main requirement is the capacity of these modules to illuminate another line-of-sight when another module is not operative by means of the use of auxiliary optical stage installed on the TB and therefore all the probe beams cover the same distance. For that, there are two areas in TB: first, the delay area is used to equalize the path lengths of all probe beams and to allow to all modules to illuminate whatever line-of-sight; second, the interchange area is where the launching mirrors steer to beams towards the input windows of the AEM40, AEN40 or AEO40 ports. For the initial operation, four SIMDIs (1, 7, 8, and 10) are chosen to illuminate four channels (ch1, ch2, ch6 and ch10) and therefore these are simulated by Zemax initially. In this work, we simulate the direct propagation from SIMDIs to the corresponding lines-of-sight to validate the simulations of these modules.

## III. RESULTS OF SIMULATIONS FOR MULTICHANNEL DISPERSIVE INTERFEROMETER BY ZEMAX.

Four SIMDI are simulated by Zemax based on the design of modules already installed on TEXTOR. Figure 2 shows the layout of a single interferometric module.

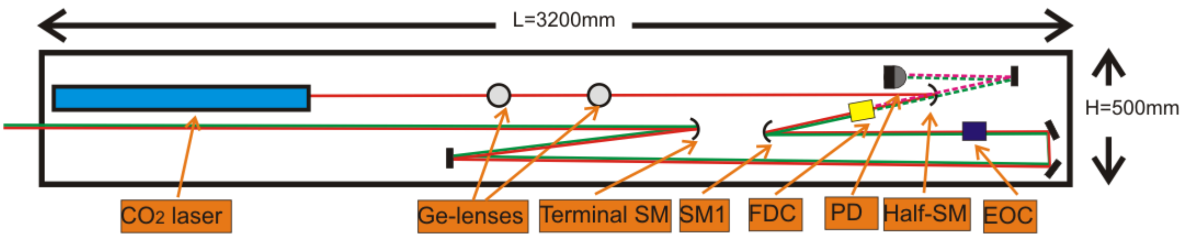


Figure 2: Layout of dispersive interferometric module for W7-X based on TEXTOR's SIMDIs [1].

The laser source is a $CO_2$ laser ($P_o$=25W, $\lambda_1$=10.6μm, 2θ=4mrad, $2w_0$=3.5 mm). After the laser beam output, a telescopic system consisting of two Ge lens ($R_1$=600mm; $R_1$=300mm) is used to obtain the adequate Gaussian characteristics of the beam before illuminating the FDC. Subsequently, a spherical half-mirror (R=420mm) is used to focus the beam into the FDC that is made of $AgGaSe_2$ (5×5×1 $mm^3$). At the output of the FDC, the fundamental beam ($\lambda_1$) and the second-harmonic beam ($\lambda_2$=5.3 μm) steer to a spherical mirror SM1 (R=405 mm) that focuses them on a GaAs electrooptical cell 10×5×50 $mm^3$ to modulate at 250 kHz. Both beams are propagating in the module and reach a spherical mirror (Terminal SM) that focuses on and steers the probe beams out the module towards the transmission bench. The radius of curvature of this last mirror for these simulations is different in each module but, for the final design, will be the same for all modules. The values of the radius of curvature for these four modules are about 4600-4900 mm. The covered distance by the beams along the TB is about

10.5 meters approximately. The beams are steered to plasma by a flat mirror placed at the end of TB and so to access to the plasma through the access window. The distance between the window and the CCR is >2.6 meters. When the beams reach the CCR, both are reflected and return to the module by the same path but slightly parallel shifted passing through the EOC and FDC. Here, a second doubled beam is generated obtaining in this way the phase information of the fundamental beam. Finally both second-harmonic beams reach a final spherical mirror (R=500mm) that focus them on a photodetector. Tables I and II show the launching/returning beam waists (w and w' respectively) of the fundamental and second-harmonic beams in the principal reference points of the optical design.

| 10.6 µm | $w_{FDC}$ | $w_{EOC}$ | $w_{WIND}$ | $w_{CCR}$ | $w'_{EOC}$ | $w'_{FDC}$ |
|---|---|---|---|---|---|---|
| SIMDI1 | 0.249 | 0.506 | 5.641 | 2.365 | 0.506 | 0.249 |
| SIMDI7 | 0.249 | 0.506 | 4.513 | 2.484 | 0.505 | 0.247 |
| SIMDI8 | 0.249 | 0.506 | 4.888 | 2.561 | 0.505 | 0.248 |
| SIMDI10 | 0.249 | 0.506 | 4.533 | 2.843 | 0.504 | 0.249 |

Table I: Beam waists of the fundamental beam (mm).

| 5.3 µm | $w_{FDC}$ | $w_{EOC}$ | $w_{WIND}$ | $w_{CCR}$ | $w'_{EOC}$ | $w'_{FDC}$ | $w_{PD}$ (1) | $w_{PD}$(2) |
|---|---|---|---|---|---|---|---|---|
| SIMDI1 | 0.176 | 0.359 | 3.972 | 1.679 | 0.359 | 0.176 | 0.177 | 0.192 |
| SIMDI7 | 0.176 | 0.359 | 3.179 | 1.649 | 0.358 | 0.176 | 0.177 | 0.192 |
| SIMDI8 | 0.176 | 0.359 | 3.444 | 1.819 | 0.358 | 0.176 | 0.177 | 0.192 |
| SIMDI10 | 0.176 | 0.359 | 3.196 | 2.019 | 0.359 | 0.176 | 0.177 | 0.192 |

Table II: Beam waists of the second-harmonic beams (mm).

It is necessary to comment the presence of little spherical aberrations in y-axis due to the use of off-axis optical systems and principally in the returning beams (the difference of the radii of curvature on the detector in x and y directions is ~370 mm). These results are compatible with the TEXTOR's SIMDIs and show the first results in order to design the optical elements of the modules excepted the last spherical mirror that allows to equalize the path length in all SIMDIs.

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