Comparison between simulation and experimental results for laser beam positions for TPC laser calibration system

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Motivation

The MPD TPC requires precise spatial calibration for accurate charged-particle track reconstruction. Its laser calibration system produces reference ionisation tracks with defined geometry in the drift volume, enabling monitoring of detector distortions, optical alignment and reconstruction accuracy. Therefore, comparing simulated and measured beam positions is essential for validating the optical model and ensuring reliable alignment of the TPC laser calibration system.

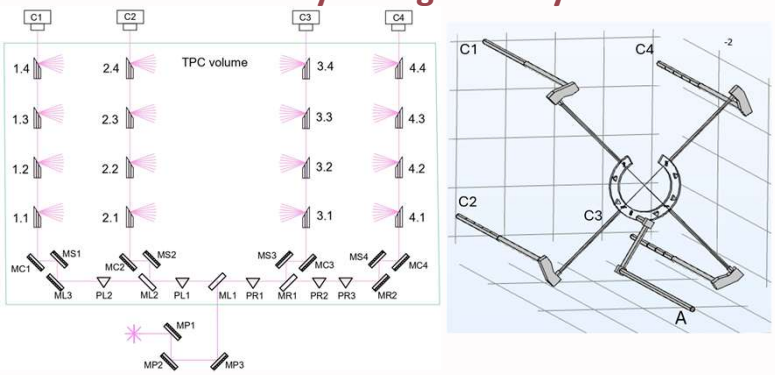
Aim

To investigate the geometry of laser-beam propagation inside the drift volume of the TPC.

Objectives

- Develop numerical model of laser pulse propagation through the TPC calibration system.
- Determine allowable mirror alignment ranges.
- Reconstruct measured beam trajectories and compare with the ideal model.

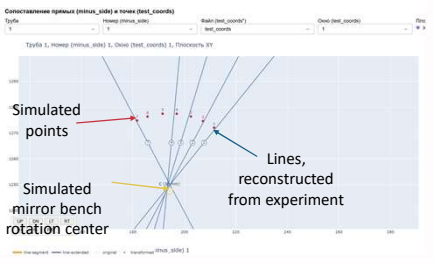
Laser calibration system geometry

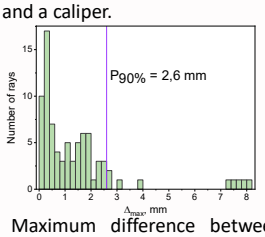


Optical scheme and 3D geometry of the TPC laser calibration system

Trajectory reconstruction

For a preliminary rapid analysis, the beam trajectories were reconstructed by adjusting the rotation angles in the assembly models to achieve the best agreement between the simulated beams and the measured beam-intersection points on the screens and Mylar sheets, as measured with a tracker and a caliper.





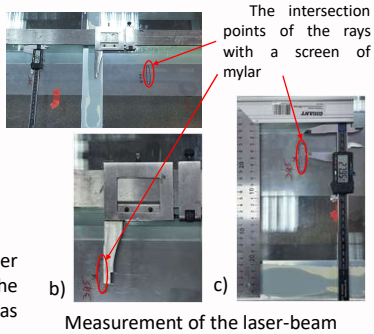
Maximum difference between simulated (ideal) and experimentally measured positions across laser beam rays

Experimental measurements



Portable Leica AT403 laser tracker

Special screens with a reflector for the laser tracker were installed at the points where the laser beams intersected. The screen was positioned at 2 distances from micromirrors – each beam is characterised by 2 sets of points.

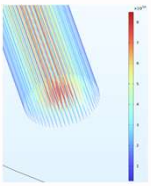


Measurement of the laser-beam intersection points with the mylar screen: a) top view; b) *X*-coordinate; c) *Y*-coordinate.

Ray-tracing method

Gaussian beam ⇨ Set of discrete beams

- Each beam has its own: power, intensity, direction, polarization.
- The optical system is described by a set of mirrors, plates, prisms, screens and micromirrors.



Comsol Multiphysics

$$\begin{cases} \frac{d\vec{k}}{dt} = -\frac{\partial \omega}{\partial \vec{r}}, \\ \frac{d\vec{r}}{dt} = \frac{\partial \omega}{\partial \vec{k}}; \end{cases}$$

ω – angular frequency;
t – time;
$\vec{k}$ – wave vector;
$\vec{r}$ – position vector.

Calculation time – (5-180) min

Python

Event-driven algorithm

Between optical surfaces, each ray propagates along a straight line:

$\vec{r}_0$ – initial point of the ray,
$\vec{e}$ – unit direction vector,
s – path-length parameter along the ray.

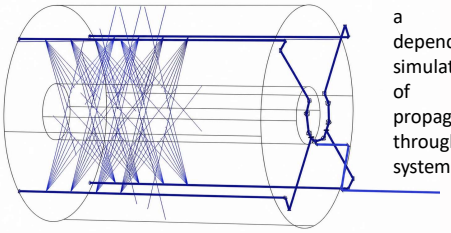
$$\vec{r}(s) = \vec{r}_0 + s\vec{e}$$

Calculation time – (10-120) s

Simulation

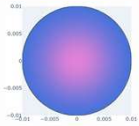
Comsol Multiphysics

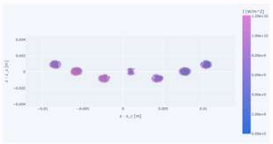
d = 20 mm
λ = 266 nm
$I_0 = 8{,}49 \cdot 10^{10}$ W/m²



a time-dependent simulation of beam propagation through the system.

The cross-section of initial radiation beam

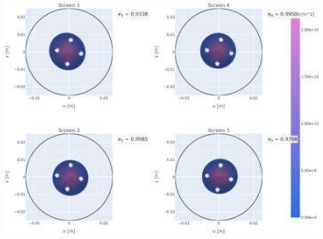




The cross-section of rays reflected from micromirrors before entering the drift volume

Python

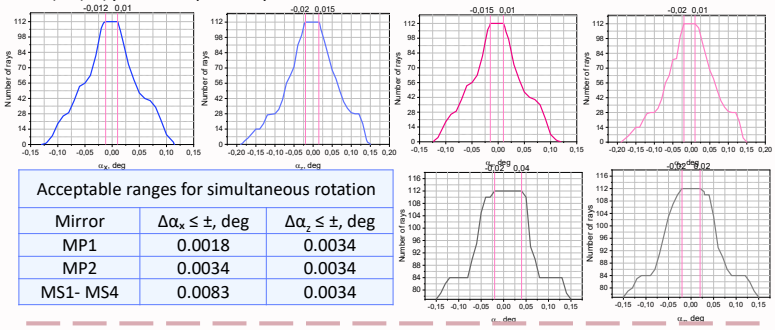
ray interactions with elements are processed sequentially as a series of simultaneous events.



Intensity distribution in the cross section of the laser beam when it hits chambers C1-C4

Virtual mirror alignment

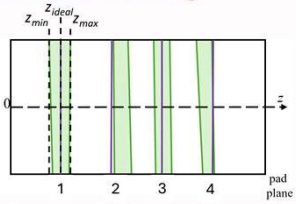
Dependence of the number of beams injected into the working gas volume of the TPC on the angle adjustment error for the mirrors separately MP1, MP2, MS1-MS4: a), c), e) *x*-axis, b), d), f) *y*-axis, respectively.



Acceptable ranges for simultaneous rotation

Mirror	$\Delta\alpha_x \le \pm$, deg	$\Delta\alpha_z \le \pm$, deg
MP1	0.0018	0.0034
MP2	0.0034	0.0034
MS1- MS4	0.0083	0.0034

Drift velocity



Side view of the ideal laser plane (purple lines), the beam divergence (green areas), which roughly match the geodetic measurements

Laser plane number	z_{ideal}, mm	z_{min}, mm	z_{max}, mm
1	333	302.05	344.66
2	666	667.64	694.06
3	999	974.10	1023.38
4	1332	1258.14	1332.61

$v_d = v_{id} = (55.3693 \pm 0.1440)\,mm/mcs$ $\quad v_{eff} = v_{id}\frac{z_{id}}{z_{real}}$

The uncertainty in laser plane positioning sets an upper limit on the drift velocity error:

$$\frac{v_{eff} - v_{id}}{v_{id}} \approx 3.5\%$$

Conclusions

- A ray-tracing model of UV laser-pulse propagation (λ = 266 nm, τ_p = 5-7 ns, d_0 = 20 mm) was developed, which enabled virtual alignment of the mirrors.
- The permissible deviation from the ideal alignment angles for mirror MP1: $\Delta\alpha_x \le \pm 0.002°$, $\Delta\alpha_z \le \pm 0.003°$; MP2: $\Delta\alpha_x \le \pm 0.003°$, $\Delta\alpha_z \le \pm 0.003°$; MS1 - MS4: $\Delta\alpha_x \le \pm 0.008°$, $\Delta\alpha_z \le \pm 0.003°$ for simultaneous rotation. Exceeding these leads to fewer beams entering the TPC volume and a deterioration in calibration quality.
- The laser beam position error was defined as the maximum distance between one of the three experimental points and the straight line fitted using the least squares method up to the position of the micromirror assembly. On average, this error amounts to approximately 0.4-2.2 mm.
- The upper possible limit of the drift velocity is around 3.5%. This indicates that the model must take into account the actual geometry of the laser tracks.
- The system will be further developed to enable automatic mirror alignment and integration of the ideal and real optical models.