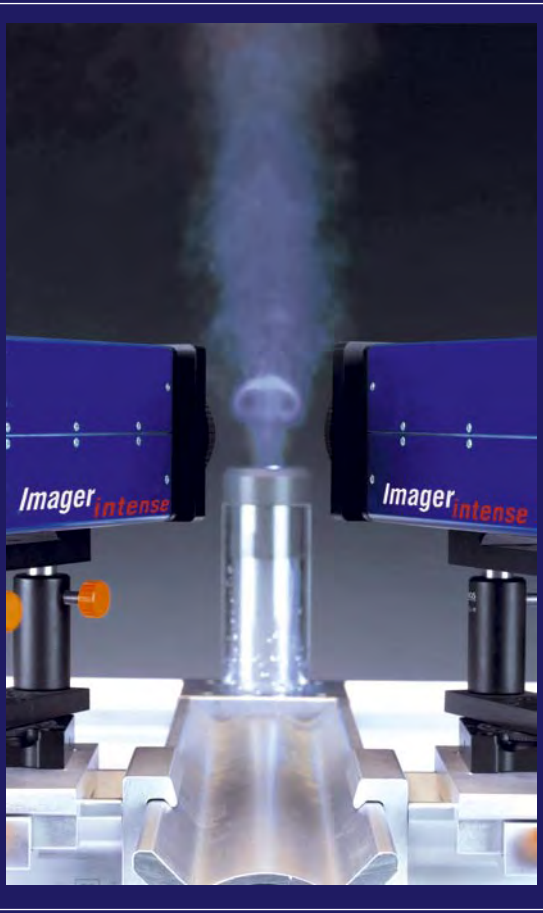
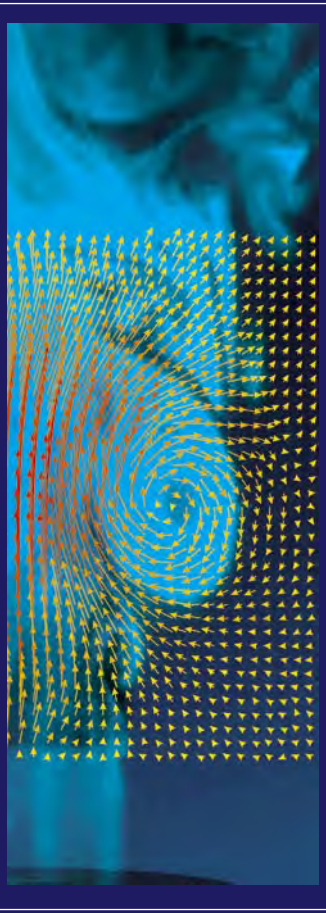




FlowMaster

Advanced PIV/ PTV Systems for Quantitative Flow Field Analysis

LaVision

We count on Photons

FlowMaster

integrated turn-key systems with unique measurement capabilities

LaVision's pioneering innovations

advanced PIV/ PTV systems

LaVision designed the most flexible and powerful commercial PIV system family **FlowMaster**, based on our application knowledge and our tradition of technical communication with our customers.

LaVision continuously offers the best PIV algorithms for calculation and validation, like deformed interrogation windows or the unique regional median filter for data validation.

1997:
- first commercially available highly sensitive **12 bit PIV** CCD camera system

1998:
- **3D-Stereo PIV** presentation at the Lisbon conference
- simultaneous 2-phase flow field analysis

1999:
- development of a new **3D-PTV** technique
- integration of a high resolution **2K x 2K PIV** camera

2000:
- **Time-Resolved PIV** to determine fluid dynamic coupling effects in **time** and **space**.
- endoscopic PIV setups
- **flow tagging** based on molecular tracers
- implementation of **mean correlation algorithm**

2001:
- **Micro PIV** for micron scale resolution
- **Dual Plane PIV** based on stereo PIV systems for determination of 3D vorticity or acceleration

2001-2005:
- successful participation in the PIV challenges, a comparison of PIV algorithms among PIV and PTV research teams worldwide

2004:
- patented PIV tool **Self-Calibration** for the correction of even large misalignments between calibration plate and laser light sheet

2005:
- **FlowMaster MITAS**: optical inverted microscope with 3D translation stage and complete computer control

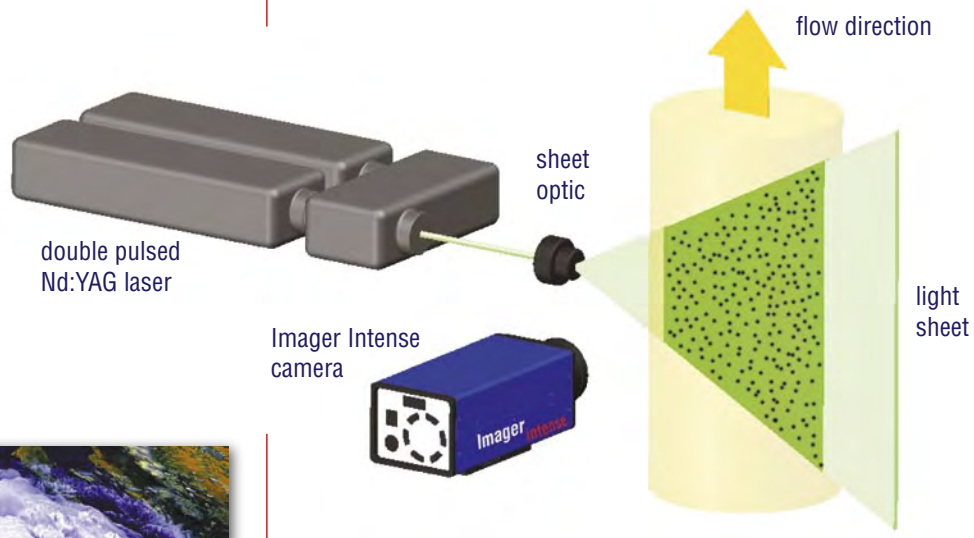
2006:
- **Tomographic (Tomo)-PIV,** a novel technique for instantaneous 3D velocity field measurements

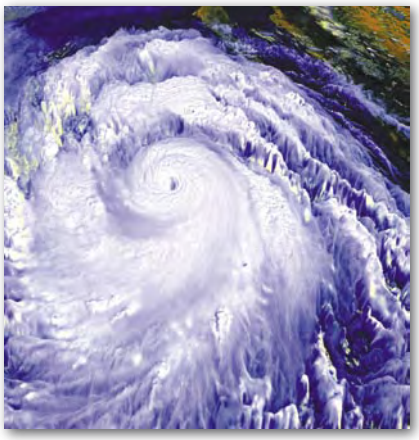
FlowMaster is part of a complete family of light sheet imaging systems designed for the investigation of combustion, spray, flow and aerodynamic applications. The versatile **FlowMaster** models are application oriented, meeting a wide range of measurement requirements due to their modular and flexible system design.

Based on a FlowMaster PIV system **Multi Parameter Laser Imaging** (velocity, size, species concentration, temperature) is possible using multi-technique approaches (PIV, LIF, Raman, Rayleigh).

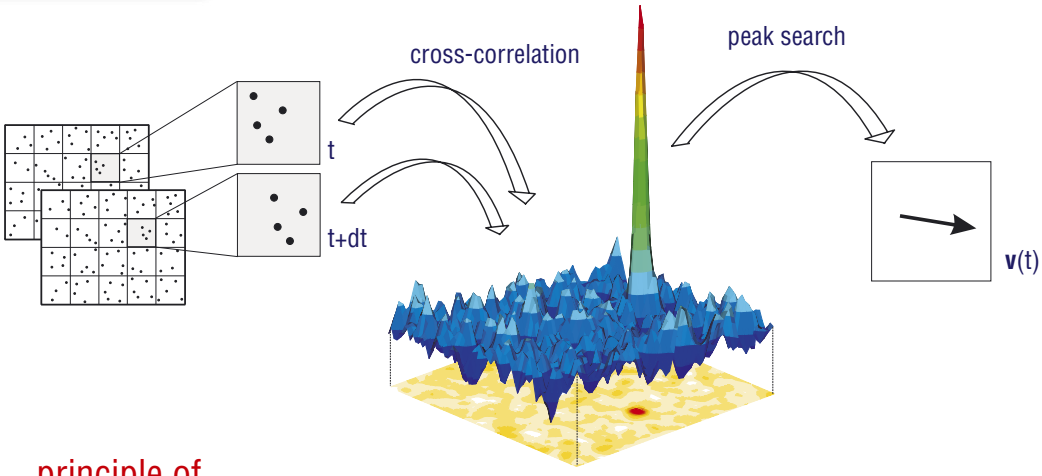
Working Principle

The **FlowMaster** system family is designed to measure instantaneous 2D- and 3D-velocity fields using the well-established Particle Image Velocimetry (PIV) technique. The flow is seeded with small particles which follow the flow. Typically a pulsed laser beam is formed into a light sheet and is fired twice with a short time delay dt. Both illuminations are recorded by one double-frame high resolution CCD camera. Image distortion due to optical path or oblique viewing is corrected automatically.





The recorded image is divided into small interrogation windows typically 64 x 64 down to 8 x 8 pixels in size. During the time interval **dt** between the laser shots the particles of each interrogation window have moved by a displacement **ds**. The velocity is then simply given by the ratio **ds/dt**. The calculation of the particle displacement **ds** is done by fast FFT-based cross-correlation of two corresponding interrogation windows. Additional advanced correlation algorithms are selectable for improved performance such as local adaptive window shift and deformation and correlation averaging.



principle of cross-correlation PIV

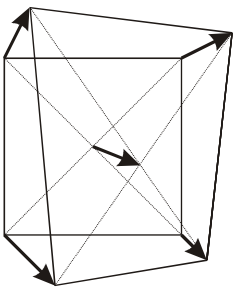
The position of the highest peak in the correlation plane indicates the mean displacement **ds** of the particles in a particular interrogation window. The displacement vectors of all interrogation windows are finally transformed into a complete instantaneous velocity map.

PIV Algorithms

innovative flow field analysis algorithms for PIV/ PTV

successful participation in PIV challenge

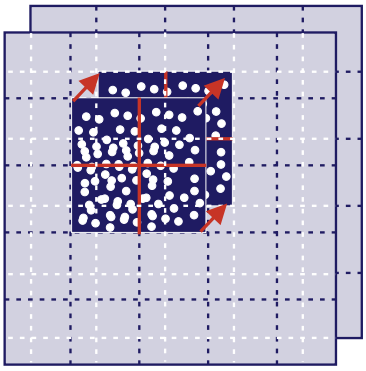
window deformation technique: the next generation of PIV analysis



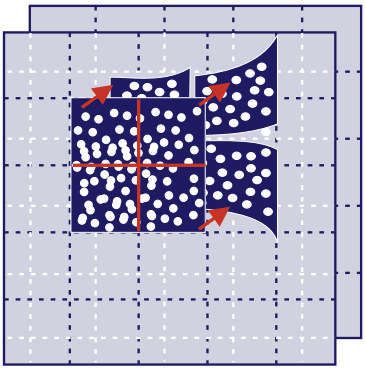
LaVision provides up to date flow analysis algorithms developed in close cooperation with various PIV research groups. The software is open for user modifications and extensions based on the built-in CL macro language, which has already been used extensively by many customers (‚C'-Syntax: all source codes are available).

The flow field analysis algorithms for evaluation of PIV measurements come with the **D**ata **a**quisition and **Vis**ualisation software package **DaVis**.
DaVis is the unique software platform for the LaVision camera based systems. Its modular structure enables an easy to use integration of new algorithms and user-built macro codes.

The **2D-PIV** software calculates the two vector components in the illumination plane. A **2D-PTV** algorithm is included in the 2D-PIV software package. **Stereo PIV** allows the computation of velocities in all 3 directions including the out-of-plane component. As an advanced feature for image processing the PIV software supports correlation with dynamically deformed interrogation windows.



standard window shift



deformed window shift

Standard PIV analysis uses square interrogation windows, but **FlowMaster** includes the ability to use deformed interrogation windows. When this option is activated the interrogation windows are deformed according to the velocity gradient of particles within one interrogation window. As an effect of the deformed interrogation window all particle pairs have the same separation. This leads to a better signal-to-noise-ratio of the correlation function and thus to a higher accuracy in the resulting vector field.

By using a multiple camera setup it is possible to obtain an instantaneous **3D-velocity** field in a complete volume using an efficient **3D-PTV** algorithm or LaVision's powerful **Tomographic** (**Tomo**)**-PIV** method. **Time-Resolved PIV**, two-phase and two-color (fluorescence) operation modes are supported by hardware and software options.

Software Features

The **FlowMaster** PIV software packages offer several features for highly accurate 2D and 3D particle image evaluation. New features are added continuously by LaVision's software engineers and our customers throughout the world using the CL macro language.
These user programmed functions are freely distributed and can be integrated into the **DaVis** software.

image preprocessing

- masking with arbitrary shape, user-defined, automatically criteria based, high-pass filter, general n x n filter
- two phase separation on structure differences
- removal of unwanted image features (e.g. reflections)

image correction

- correction of image distortions: self-calibration procedures for 2D-PIV for angular viewing and 3D-Stereo PIV

PIV algorithms

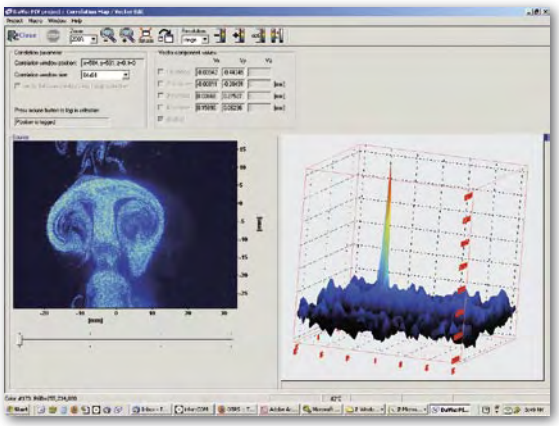
- various auto- and cross-correlation functions: standard FFT, normalized
- advanced 2D- and 3D-particle tracking algorithms for lower seeding density
- second-order correlation
- vector calculation by sum of correlation planes of n images
- adaptive multi pass (highest resolution and stability)
- high accuracy (no peak locking)
- correlation with dynamically deformed interrogation windows

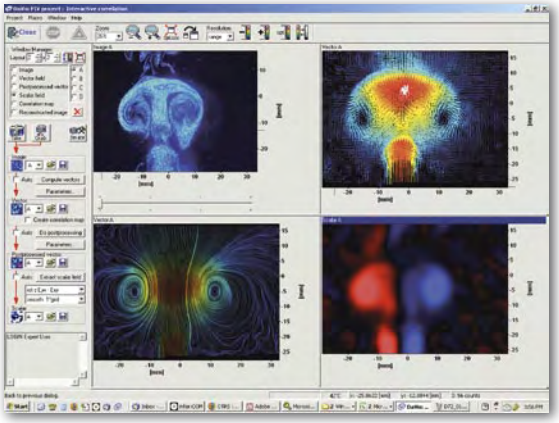
vector postprocessing and validation

- correlation peak height ratio filter
- local and regional median filter incl. replacement with second choice vectors
- global vector magnitude filter
- smoothing and interpolation

vector field processing

- scalar fields: rotation, divergence, stress
- statistics: mean, rms, PDF, scatter plots
- contour maps, streamlines, streaklines
- vortex analysis: center, strength and velocity
- space and space-time correlation
- user-defined operations
- proper orthogonal decomposition (POD)





DaVis – the graphical user interface to PIV algorithms

Application Fields

FlowMaster systems have been successfully used to investigate a wide range of flow phenomena occuring in science and engineering, as well as in biological and medical applications. Using **FlowMaster**, PIV can be applied to gaseous and liquid flows and even to multiphase or reactive flows like combustion.

wide range of aero- and hydrodynamic flow applications

courtesy: DLR Göttingen

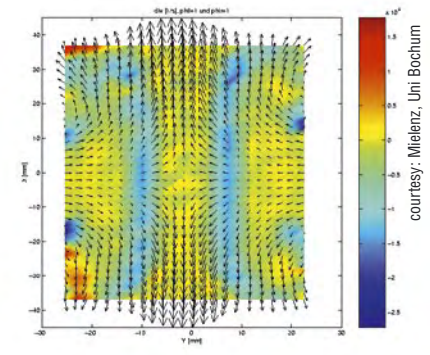
Ludwig Prandtl operating his water channel in 1904

Aero- and Hydrodynamics

- 3D-velocity field using stereo imaging
- multi camera support
- measurement of acceleration fields based on dual plane stereo PIV
- automatic calibration procedure
- improvement of flow analysis near surfaces by effective stray light suppression
- time resolved and high resolution PIV

IC-Engine Flow

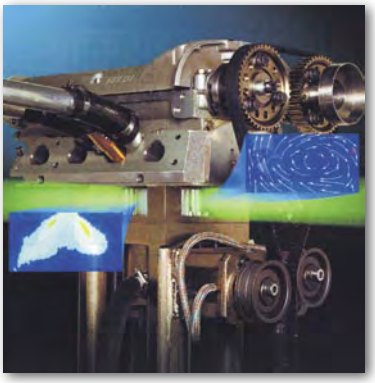
- phase-locked measurements of in-cylinder flow
- readout of encoder signal
- small optical access for laser light sheet and camera through small holes with endoscopic methods



courtesy: Mielenz, Uni Bochum

flow field of two flat flames in counterflow

synchronized IC-engine flow investigations



courtesy: FEV

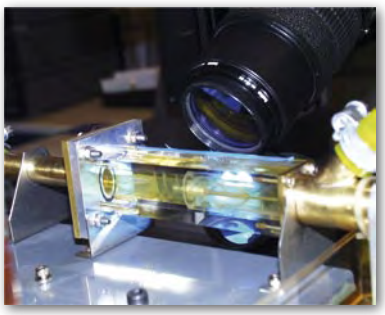
IC-engine flows

Reactive Flows

- correlation with temperature field
- seeding with high temperature resistant TiO_2 particles
- molecular tracer detection

Biomedical Applications

- monitoring of blood flows in veins and arteria
- microfluidic imaging systems to improve the blood flow around heart valves.



courtesy: Berlin Heart AG

Stereo PIV in the model of an implantable blood pump

Upgrades

courtesy: DNW (German-Dutch Wind Tunnels)

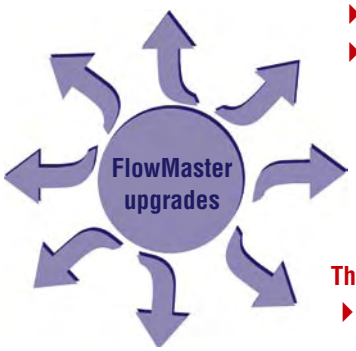
FlowMaster basic 2D-PIV systems can easily be extended to application for more sophisticated flow problems. **Stereo** or **Tomo-PIV** are offered for more detailed flow analysis. **FlowMaster** can be upgraded to a combined **PIV-LIF system**, e.g. LaVision´s **SprayMaster** or **FlameMaster** system. For this purpose the **FlowMaster** cameras can be utilized with image intensifiers.

Stereo PIV
- 3 velocity components in the light sheet

FlameMaster
- OH, NO - formation
- species distribution
- temperature fields
- air/fuel ratios
- soot formation

Tomographic PIV
- 3D3C-vector field in a complete volume
- fully digital recording and processing

Microscopic PIV
- PIV for micro scales



SprayMaster
- patternation
- drop sizing
- evaporation

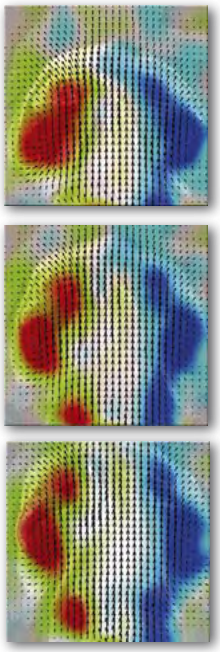
Dual Plane PIV
- upgrade from stereo PIV: 3D-vorticity, acceleration

Thick-sheet stereo PIV
- Tomographic sheet reconstruction
- 2 vector planes by 3D-cross-correlaton
- full 3D gradient tensor

PIV-LIF Combination
- e.g. 2-color PIV
- multi phase flows
- PIV + OH-LIF, NO-LIF

The extended system functionality given by the various upgrades is well integrated into the DaVis software environment.

FlowMaster
Time-Resolved PIV



high speed PIV image sequence

FlowMaster High-Speed opens new areas of fluid dynamic analysis. It combines the spatial information of digital PIV with the temporal evolution of each point.
The system measures velocity and acceleration fields and turbulence quantities of transient phenomena. The time-resolved PIV information opens a new area for velocity derivations or correlations in time. With time-resolved PIV the user is able to calculate temporally dependent quantitative turbulence information. It provides information about:

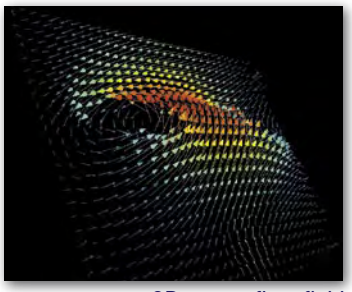
- time dependence of POD-modes
- vortex characteristics with time
- space-time correlations
- flow element tracking
- power spectra
- acceleration fields
- flow time scales

LaVision‘s **FlowMaster High-Speed** systems include state-of-the-art digital high-speed cameras with up to 5 kHz frame rate at full resolution of 1k x 1k pixel and up to several 100 kHz frame rate at reduced resolution. Single or dual cavity high-repetition rate solid state lasers up to 50 mJ per pulse are available. All components are integrated and controlled from the **DaVis** software.

FlowMaster
3D-Stereo PIV

remote control of Scheimpflug condition, aperture, focus

stereoscopic imaging



3D vortex flow field

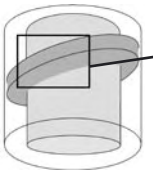
FlowMaster 3D is a straight forward extension of the **FlowMaster** 2D concept and enables the measurement of all three velocity components inside a light sheet.

FlowMaster Scheimpflug setup

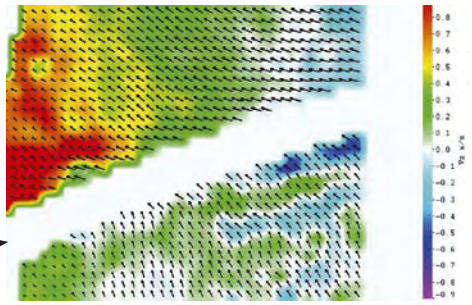
3D-Stereo PIV is based on the principle of stereoscopic imaging: two cameras capture the image of the illuminated flow particles from different angles. Scheimpflug lens arrangements keep all areas of the image planes in focus. While one camera can only measure the projection of the particle movement perpendicular to its optical axis, the combination of two camera projections enables the reconstruction of the "real" particle displacement inside the measurement volume. In this way a complete set of vectors containing all three velocity components is recorded. This setup is called **Stereo PIV** and uses the same principle as human eyesight.

Self-Calibration

Patented PIV Tool



measurement area



single vector field (color = w-component)

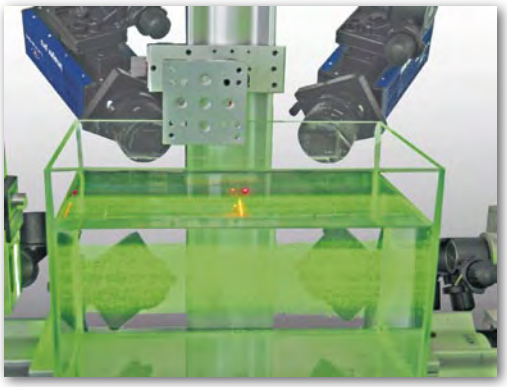
The **Self-Calibration** method is a unique, patented tool for **3D-Stereo PIV** to correct even large misalignments between calibration plate and laser light sheet. It is a standard feature of the **DaVis Stereo PIV** software package.
With **Self-Calibration** the exact location and thickness of all planes in space are determined by computation of disparity maps on the recorded particle images. In addition the disparity vectors are used to correct any remaining optical distortions not accounted for by the initial volume mapping function. **Self-Calibration** does not require that the calibration target is placed within the flow field. Internal flows such as biomedical flows, micro channels or internal combustion engine cylinders where insertion of a calibration target is impractical or impossible, can now be measured using stereo PIV techniques.

advantages

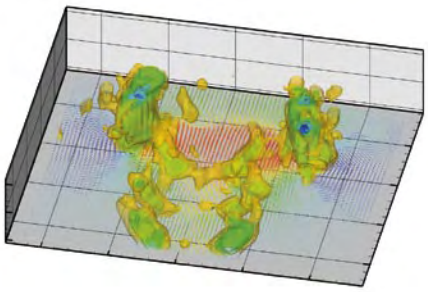
- **ultimate accuracy**: elimination of calibration errors
- **user-friendly:** free positioning of calibration plate, no need to align calibration plate exactly with light sheet
- **easy volume-scanning:** all scanning positions calibrated at once
- **ex-situ calibration**: calibration plate outside the measurement volume
- **time-saving:** calibration can be prepared off-site

FlowMaster
Tomographic PIV

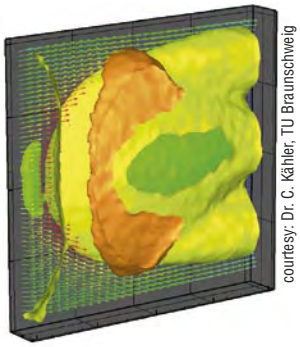
instantaneous 3D3C-vector field in a complete volume



Tomographic Particle Image Velocimetry (**Tomo-PIV**) is a novel technique for 3D velocity measurements. Velocity information results from three-dimensional particle pattern cross-correlation of two reconstructions obtained from subsequent exposures. The technique is fully digital and allows relatively high seeding (information) density and provides dense vector fields compared to sparse 3D-particle tracking. The method is truly instantaneous across the volume, as opposed to scanning PIV and is suited for fast flows requiring small dt's between exposures and allows an easy extension to high time resolution using high speed cameras.



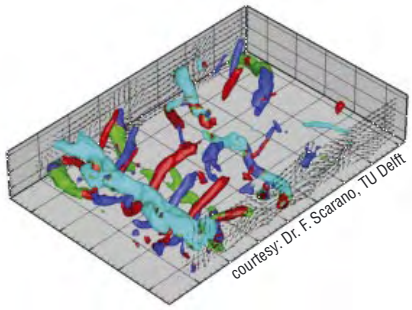
ring vortex in air



horizontal velocity iso-surfaces of flow across top of cylinder stub

applications

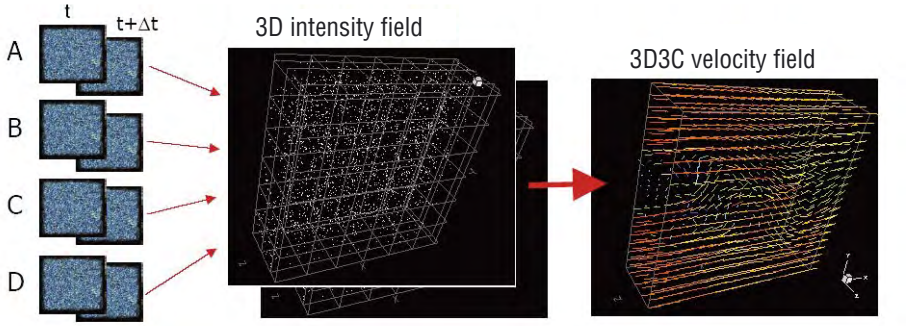
- turbulence research
- 3D-flow structure visualization
- full 3D-vortex analysis
- flow-structure-interaction



vorticity iso-surfaces of Karman street at Re= 540

principle of Tomographic PIV

Tracer particles within the measurement volume are illuminated by a high power pulsed light source and the scattered light pattern is recorded simultaneously from typically 4 viewing directions using CCD cameras. The 3D particle distribution is reconstructed by a tomographic reconstruction algorithm (MART) as a 3D light intensity distribution for each voxel. The particle displacement within a chosen interrogation volume is then obtained by the 3D cross-correlation of the reconstructed particle distribution at the two exposures, using advanced iterative multi-grid algorithms with deformed interrogation volumes.



FlowMaster
Endoscopic PIV

camera and laser endoscopes for limited optical access

laser endoscope

camera endoscope

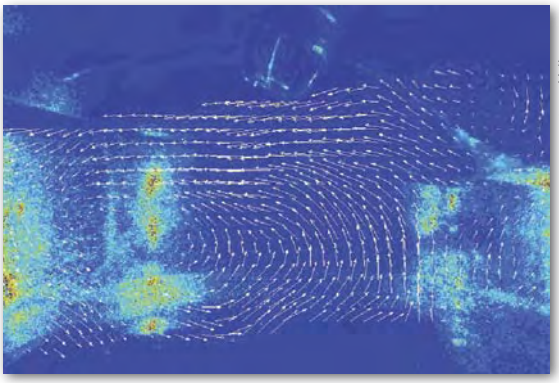
applications

PIV measurements in IC engines, turbo machinery or pumps usually require the manufacturing of costly prototypes with large windows to gain optical access. Using LaVision's endoscopic PIV system has enormous advantages in these experiments. Small optical access of only 8 mm holes enables PIV measurements in a much easier way and therefore reduces the costs and complexity of the required prototype.

special endoscope setup

LaVision´s **laser endoscope** generates a laser light sheet from a high power pulsed laser. It is designed to fit at the outlet of the **Laser Guiding Arm** (articulated arm) and consists of a thin steel tube at the end.
Image acquisition is done by a specially developed **camera endoscope** which can easily be mounted to a **FlowMaster** series camera together with a lens.

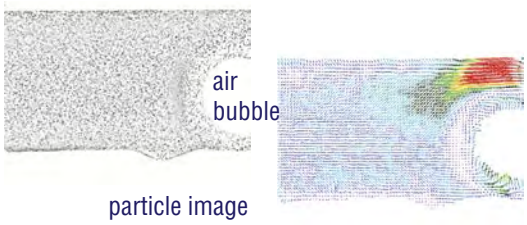
- internal aerodynamic phenomena
- turbomachinery, aircraft engines, compressors, pumps
- IC engine flows, tumble and swirl studies
- reactive flow fields, industrial reactors, combustion studies
- pharmaceutical and medical applications



courtesy: Volkswagen

tumble flow in IC engine

FlowMaster
Micro PIV



particle image

vector field

micro channel with air bubble

conventional PIV applied to microscopic systems

FlowMaster
MITAS

inverted laser imaging microscope with joy stick

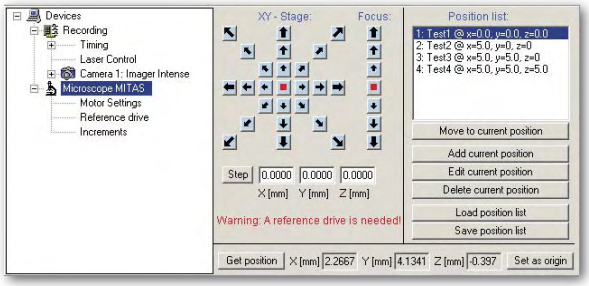
The **FlowMaster Micro PIV** Systems are designed to measure velocity fields of particle seeded flows with micron scale spatial resolution using PIV techniques.

Micro PIV setup

The light source is a double pulsed Nd:YAG laser that is focused by an epifluorescent microscope with a high numerical aperture on a microfluidic device. The microflow is seeded with fluorescent particles. A microscope lens collects the particle signal that has a longer wavelength than the illuminating light. This signal is separated from the laser light by a filter cube and is recorded by a **FlowMaster** series camera. The double frame images are evaluated with conventional PIV algorithms.

The **FlowMaster MITAS** laser imaging system comprises a fully motorized 3-axis microscope stage with a high performance controller and a high precision microscope objective. For standard applications a small DPSS laser for pulsed illumination and a highly sensitive, dual-frame multiple-exposure CCD camera is used. A system PC with built-in synchronization unit controls the complete laser imaging system. LaVision's modular **DaVis** software is used for advanced image acquisition and data analysis.

The xyz (focus)-traverse system can be operated manually using a joystick or the device control manager in **DaVis**, which contains a position list with a number of positions. Every position can be added, edited and deleted and an **easy repeatability of each position** is guaranteed after e.g. lens exchange.



position list in the main dialog of DaVis

The light is delivered through an optical fiber to the microscope. A built-in pilot LED is used for target focusing. The filter cube exchange box allows a fast adaptation for different excitation and emission wavelengths.

FlowMaster
System Components

Depending on the application LaVision's **FlowMaster** systems integrate different laser light sources and cameras:

PIV cameras	Imager Intense	Imager pro X 2M	Imager pro X 4M	Imager pro X 11M	HSS 5	HSS 6
resolution [pixel]	1376 x 1040	1600 x 1200	2048 x 2048	4008 x 2672	1024 x 1024	1024 x 1024
frame rate@max. resolution	10 Hz	30 Hz	14 Hz	5 Hz	3 kHz	5,4 kHz
pixel size [µm]	6.45 x 6.45	7.4 x 7.4	7.4 x 7.4	9.0 x 9.0	17 x 17	20 x 20
min. time interval (dt)	500 ns	110 ns	115 ns	210 ns	2 µs	4,8 µs
dynamic range	12 bit	14 bit	14 bit	14 bit	10 bit	12 bit

For maximum sensitivity intensified, gated versions with modular lens-coupling between CCD camera and image intensifier are available.

imaging optics
- Scheimpflug lens mounts for oblique viewing (remote controlled!)
- camera endoscopes
- long distance microscopes
- epi-fluorescent microscopes for Micro PIV

filter
- small bandwidth for background suppression

beam delivery
- Laser Guiding Arm
- multi-purpose high power mirrors
- laser endoscopes

light sheet optics
- adjustable focus and divergence
- wide angle setups

triggering
- synchronization for all operation modes
- versatile, programmable PC-based timing unit PTU
- 32 trigger channels
- ready on demand by external trigger
- phase-locked measurements

processor
- parallel processing (multi processor computers)
- multiple computer setups (master/slave configurations)
- Windows XP Operation System

accessories
- seeding generators and particles
- stepper motors and traversing systems for scanning
- work benches
- external mechanical shutter

laser
- double-pulse Nd:YAG laser systems from different suppliers covering a wide range of output energy

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