Measuring Techniques at the High-Speed Cascade Wind Tunnel of the University of the Federal Armed Forces Munich

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Abstract

The present paper deals with the measuring techniques which have been established at the High Speed Cascade Wind Tunnel since starting of the research work in November, 1985. Due to the fact that the open loop wind tunnel with the open test-section is installed within a cylindrical vacuum-tank special techniques were necessary for the measurement systems. In addition to fully computer controlled wake and profile pressure distribution measurements and Schlieren-measurements with all optical equipment outside the vacuum-tank advanced measuring techniques like laser-two-focus velocimetry and heated thin-film as well as hot-wire measurement systems have been installed and are described in this report.

Nomenclature:

a) Symbols:

Cp	[-]	$p(X/L)-p_K \, / \, q_{2th}$
d/l	[-]	relative blade thickness
DP	[Pa]	$p_1 - p_2$
DPT	[Pa]	$p_{t1} - p_{t2}$
ΔT,DELTAT	[K]	overheat ratio
E/L	[-]	relative distance of the plane for wake measurements from the trailing edge of the blades
E	[V]	DC-component of the anemometer signal
EEFF	[mV]	AC-component of the anemometer signal
H	[mm]	test section height
l,L	[mm]	chord length
Ma,MA	[-]	Mach number
OMEGA	[-]	axial flow density
n	[rpm]	number of revolutions per minute
p	[Pa]	static pressure
p_t	[Pa]	total pressure
P	[kW]	electrical power
P_1	[kW]	power of first vacuum pump
P_2	[kW]	power of second vacuum pump
q	[Pa]	dynamic pressure
$\dot{q}$	[W]	heat flux
R	[Ω]	resistance
Re,RE	[-]	Reynolds number
t/l, T/L	[-]	relative blade spacing
Tu,TU	[%]	degree of turbulence
τ	[N/mm^2]	shear stress
$\dot{V}$	[m^3/s]	air flow rate
X/L	[mm]	relative chord lenth
β,BETA	[°]	flow angle
β_S	[°]	stagger angle
$\Delta\beta_{corr}$	[°]	flow angle correction
π	[-]	compressor total pressure ratio

b) Indices:

0	no flow condition
1	upstream condition
2	downstream condition
2th,2TH	downstream condition for isentropic flow
K	within the vacuum-tank
ST	sensor overheated
u, U	probe position within the wake
w	wall

c) Abreviations:

BS	Braunschweig
DFVLR	Deutsche Forschungs- und Versuchsanstalt fuer Luft- und Raumfahrt
HP	Hewlett Packard
M	München
PSI	Pressure Systems, Inc.
VERNR.	test number

1. Introduction

The rebuilding of the High-Speed Cascade Wind Tunnel of the University of the Federal Armed Forces Munich, which was formerly in operation at the DFVLR in Braunschweig was finished in November 1985 as reported at the last symposium in Genoa (/1/). After some calibration tests the establishment of different measuring techniques and of a modern data aquisition system started simultaneously with the research work:

- The laminar-turbulent transition of the profile boundary-layer is investigated by profile pressure distribution and heated thin-film measuring techniques.
- With respect to the influence of blade aspect ratio on secondary losses investigations are done by traversing a probe along the blade height using variable side-walls and measuring the wake pressure distribution.
- The influence of profile pressure distribution on secondary losses in turbine cascades is investigated by hot-wire and laser-two-focus velocimetry.
- Also flow field measurements in highly loaded compressor cascades including boundary-layer control are performed with the laser-two-focus velocimetry technique.

The establishment of most of these measuring techniques is nearly finished.

2. High-Speed Cascade Wind Tunnel

After disassembly of the High-Speed Cascade Wind Tunnel (Fig. 2.1) in Braunschweig some constructional changes were made, e.g. a longer settling chamber in front of the nozzle and a larger vacuum tank. Because of these changes and for an evaluation of former measurements obtained in the cascade wind tunnel at the DFVLR in Braunschweig calibration tests were carried out with the turbine cascade T 106 (Fig. 2.2,/2/). Fig. 2.3 shows good agreement of the wake and profile pressure distributions at design point. Only at a high negative incidence (Fig. 2.4) the profile pressure distribution differed slightly on the pressure side from the results measured in Braunschweig.

The reason was an uncorrect inlet flow angle compared to the measurement carried out in Braunschweig: Due to the fact that the angle between the horizontal line and the main flow vector $\Delta \beta_{corr}$ is important for a correct inlet flow angle, investigations were done with the turbine cascades T1 and T3 measuring the exit angle with the exit flow direction to the top and to the bottom of the vacuum tank (/3/). The difference in the exit angle is assumed to be

$$\Delta\beta_2 = 2\ \Delta\beta_{corr}$$

The result of $\Delta\beta_{corr} = -0{,}7°$ (<u>Fig. 2.5</u>) differed from measurements done in Braunschweig ($\Delta\beta_{corr} = +0{,}5°$) by 1,2°.

For the interpretation of profile pressure distributions and the boundary-layer behaviour it is important to know the inlet flow conditions, i.e. total and static pressure, turbulence intensity and total temperature distributions.

At the High-Speed Cascade Wind Tunnel the turbulence intensity of the flow is generated by turbulence grids in the inlet part of the nozzle. Calibrations for different grids were performed at the DFVLR in Braunschweig (/4/). A new calibration with hot-wire probes will be done in the next future.

Pressure and temperature distribution measurements of the inlet flow had been carried out with a five-hole-probe and a Kiel-probe (/5/). These measurements showed a nearly constant pressure distribution in the relevant area of the inlet flow. Only the temperature distribution, which is evident for hot-wire and heated-film measurements, showed a change of 1 K during a test run and a local maximum deviation of 8 K.

3. Measuring Techniques

3.1 Wake and Profile Pressure Distribution Measurements

Until now the wake and profile pressure distribution measurements at the cascade wind tunnel were done with the data aquisition system of the DFVLR (/6/). This system is replaced now by a modern system with online evaluation and high adaptibility on the different measurement concepts.

Fig. 3.1 gives a general view of this system. The most evident feature is the separation of the pressure measurement from the control and evaluation system which gives a great flexibility and easy handling.

The pressure measurement system consists of a slave computer HP 9817 which controls the multiprogrammer HP 6944S and the reference and calibration pressure unit. The pressures are measured by PSI-ESP-32 modules with 32 piezoelectrical transducers and built-in multiplexer and amplifier. These modules have an online calibration ability during the measurements. A piston inside the modules closes all pressure ports and a calibration can be carried out with a common pressure via the reference or calibration port of the modules (Fig. 3.2).

The slave computer and with it the pressure measurement system is controlled by the host computer of the test facility, a 32 bit computer Perkin Elmer 3203 with 4 MB main storage. Also the 3-axis traverse system for the wake measurements is controlled by this computer.

After the measurements of all relevant pressures evaluation is carried out with the exact impulse method (/7/) and the results are displayed on the graphics screen.

3.2 Schlieren-Measurements

For investigation of shocks in transonic cascades a Schlieren-measurement system is built up. In order to be able to focus the system during test runs all optical equipment is installed outside the vacuum-tank. Therefore two further Schlieren windows in the vacuum-tank are necessary in addition to the windows in the sidewalls of the cascade (Fig. 3.3). The optics are built up in a z-type arrangement and the light source is optional a Xenon-lamp or a strobe. Qualitative online interpretations are possible with a screen, documentation can be done with a photo-camera. A video-system is in planning.

3.3 Laser-Two-Focus Velocimetry

For the above mentioned research topics of the institute it is essential to measure the velocity vectors in cascades, especially in the blade passages including profile and sidewall boundary-layers. Because of the advance in noninstrusiv measuring techniques and with respect to the fact, that this measurement system should also be used in rotating systems at the turbomachinary test facility of the institute, a laser-two-focus system was installed at the High-Speed Cascade Wind Tunnel.

The most serious problem of this experimental set-up were the environmental conditions for such a system inside the vacuum-tank of the cascade wind tunnel: pressure down to 50 mbar, temperature up to 60°C. The first concept with the laser inside the tank had to be given up, because there is no laser available for these conditions.

A new development for the laser-two-focus velocimeter of Polytec (licensed by the DFVLR (/8/), avoids this problem by installing the laser outside the vacuum tank and using a single mode fiber optic cable to guide the light from the laser to the optical head inside the tank. This technique is in principle not a new development, but in most cases there are problems with the fiber optic coupler.
With the coupler of Polytec (Fig. 3.4) a very exact and quick

adjustment is possible: two piezo electric elements controlled by potentiometers in the launcher controller are used for angular adjustment. The piezos have a sufficient range to realign the launcher during normal operation. First measurements show an output power of 60% of the laser power projected into the fiber.

A general view of the laser-two-focus system at the cascade wind tunnel is shown in Fig. 3.5: The light from the laser Lexel 95 (2 W multiline) is guided via a 13 m fiber optic cable to the watercooled and ventilated optical head, which is inside the vacuum-tank on a 4-axis traversing system. The transceiver lens of the optical head has a working distance of 270 mm. Light scattered by particles passing through the probe volume is collected by the outer part of the lens and directed to the two photomultipliers which are connected with the signal processing unit outside the cascade wind tunnel.

The traversing system driven by stepper motors is controlled by a computer HP 9856, which can also operate as a controller of the velocimeter. Furthermore it is used for data storage as well as graphical presentation of the results. The software development is nearly finished and first measurements with the laser-two-focus system will be carried out with a turbine cascade this year.

3.4 Heated Thin-Film Measurements

The condition of a boundary-layer (laminar, transitional or turbulent) can be determined by measuring the mean and fluctuating component of the heat transfer rate /9/. The experimental set-up of this technique for investigating boundary-layers on cascades at the High-Speed Cascade Wind Tunnel is similar to that published in /10/ (Fig. 3.6). The sensors used are developed and manufactured by MTU Munich /11/. Investigations are carried out to detect the transition region and laminar separation bubbles on turbine and compressor cascades at the High-Speed Cascade Wind Tunnel. This technique shows the transition region quite satisfactorily. Investigation of shock/boundary-layer interaction is planned.

The electrical behaviour of each sensor is calibrated in an oven. Until now the signal of 48 thin-film sensors heated sequentially by a DISA 55M-system anemometer can be measured. The anemometer output signal is investigated by visual display and plot of a scope. Typical plots of the scope and results obtained by the frequency analyzer on the turbine cascade T 106 (Fig. 2.2) are shown in Fig. 3.7. The plots of the scope and frequency analyzer indicate clearly the transition. The DC component of the signal is evaluated by

$$A * \tau_w^{1/n} = \frac{\dot{q} - \dot{q}_0}{\Delta T} = \frac{1}{\Delta T} * \left(\frac{E^2}{R_{ST}} - \frac{E_0^2}{R_{ST0}} \right)$$

where $\dot{q}$ is the heat transfer rate while test-running and $\dot{q}_0$ is the heat transfer rate at zero flow conditions. The evaluation of the AC and DC components of the signals which are compared with the measured pressure distribution at the profile corresponding to Fig. 3.7 is shown in Fig. 3.8.

The pressure distribution shows a small separation bubble with turbulent reattachment. Therefore the transition takes place via a separation bubble. This is also indicated by the relative position of the TAU-wall minimum and the begin of the increase of the AC component of the signal. We found if the begin of the increase of the AC component takes place in or downstream of the TAU-wall minimum, that there exists a separation bubble. In all cases where the pressure distribution indicated no bubble, the increase but not the maximum of the AC component (equivalent to the turbulence level), takes place upstream of the TAU-wall minimum. The scattering of the plotted points is rather small, even though no TAU-wall calibration was performed.

3.5 Hot-Wire Measurements

The hot-wire anemometry at the High-Speed Cascade Wind Tunnel will be used at first for turbulence level measurements. In addition velocity measurements within the blade passage of a turbine cascade are planned.
Because of the temperature variations in the inlet flow as

mentioned before temperature compensated sensors are used with a symmetrical anemometer bridge. For setting various Reynolds-numbers the pressure inside the tank can be adjusted. The hot-wire measuring system is calibrated and linearized for each tank pressure. In order to decrease sensor damage dust-filters are installed in the suction area of the vacuum-tank.

The experimental set-up for hot-wire measurements at the High-Speed Cascade Wind-Tunnel (Fig. 3.9)is similar to the heated thin-film technique (Fig. 3.6). The system is designed for analog evaluation of the anemometer output signal. The possibility exists for frequency analysis and visual display of the signal. A TSI linearisator is used for turbulence measurements. The AC and DC voltages are measured by two digital integrating voltmeters.

4. Conclusions

At the High-Speed Cascade Wind Tunnel of the University of the Federal Armed Forces Munich advanced measuring techniques have been established for investigations on design philosophies of multistage axial turbomachines, new design concepts for turbomachine bladings and boundary-layer control in turbomachines:

- fully computer controlled measurements of wake and profile pressure distributions including online evaluation
- Schlieren-measurements
- laser-two-focus velocimetry with laser light transmission via fiber optic cable
- heated thin-film measurements
- hot-wire measurements

Because of the design principle of the cascade wind tunnel inside a vacuum tank some special arrangments had to be done for applying these measuring techniques. First results obtained with the described experimental set-ups will be published in the near future.

5. References

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UniBw München
Institut für Strahlantriebe

High-Speed Cascade Wind-Tunnel

1985

test section data:

- Mach number : $0.2 \le Ma \le 1.05$
- Reynolds number : $10^6 m^{-1} \le Re/l \le 1.5 \cdot 10^7 m^{-1}$
- degree of turbulence : $0.3\% \le Tu_1 \le 6\%$
- upstream flow angle : $25° \le \beta_1 \le 155°$
- blade height : 300 mm

supply units:

- evacuating unit : $P_1 = 30$ kW, $P_2 = 20$ kW
- boundary layer suction (centrifugal compressor) : P = 155 kW
- additional air supply (screw compressor) : P = 1000 kW

wind-tunnel data:

- a.c. electric motor : P = 1300 kW
- axial compressor (six stages):
  - air flow rate : $\dot{V} = 30\ m^3/s$ (max.)
  - total pressure ratio : $\pi = 2.14$ (max.)
  - number of revolutions : n = 6200 rpm (max.)
- tank pressure : $0.05\ bar \le p_k \le 1.2\ bar$

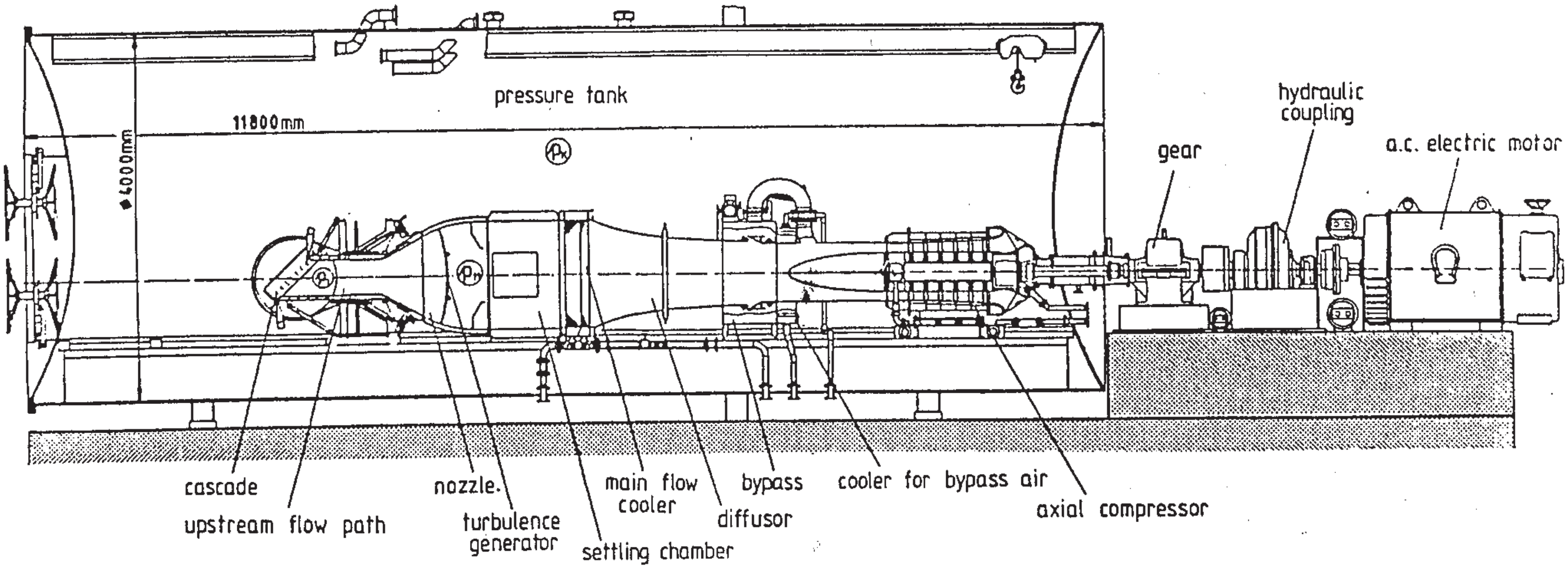


Fig. 2.1: The High-Speed Cascade Wind Tunnel

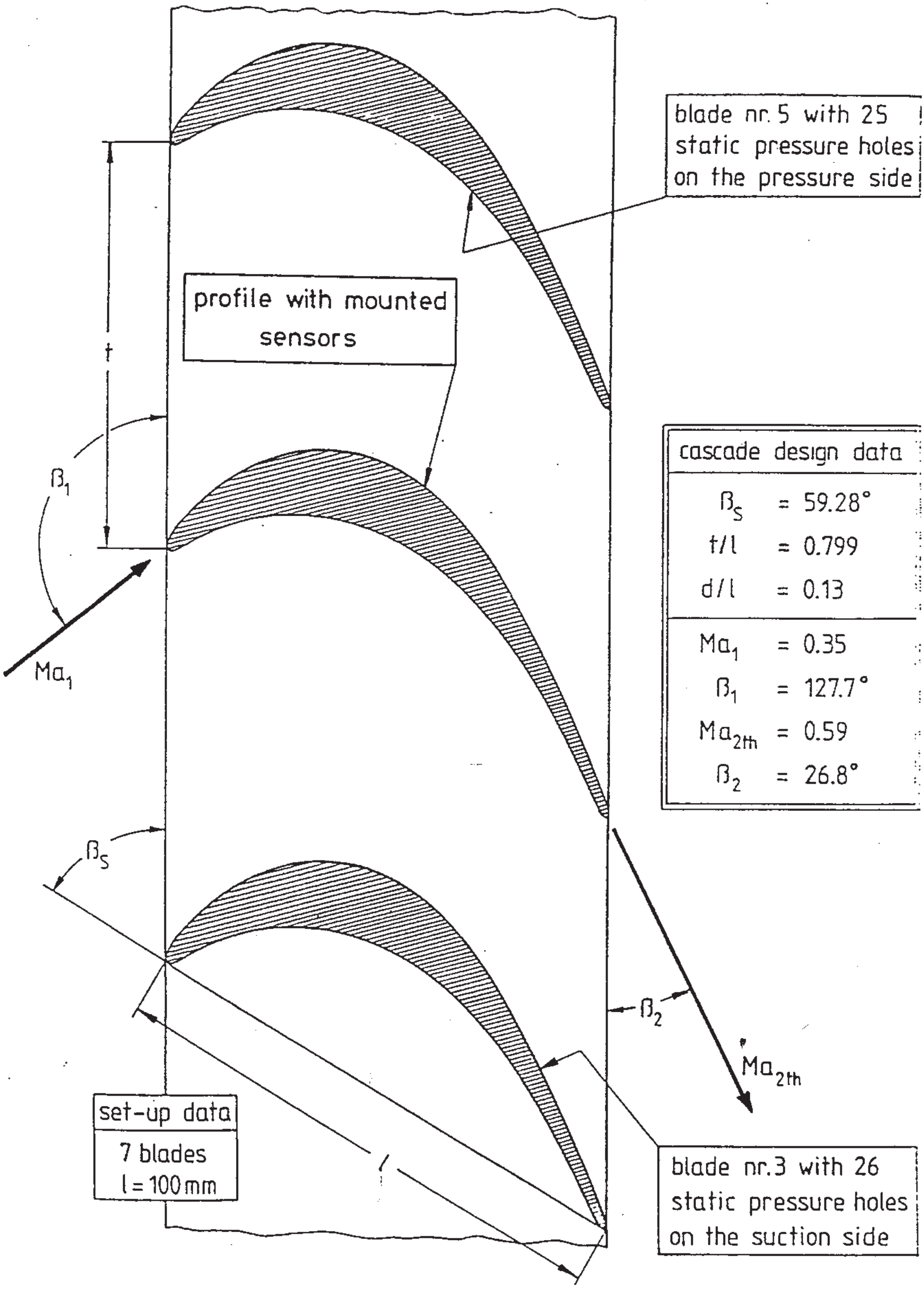


Fig. 2.2: Turbine cascade T 106

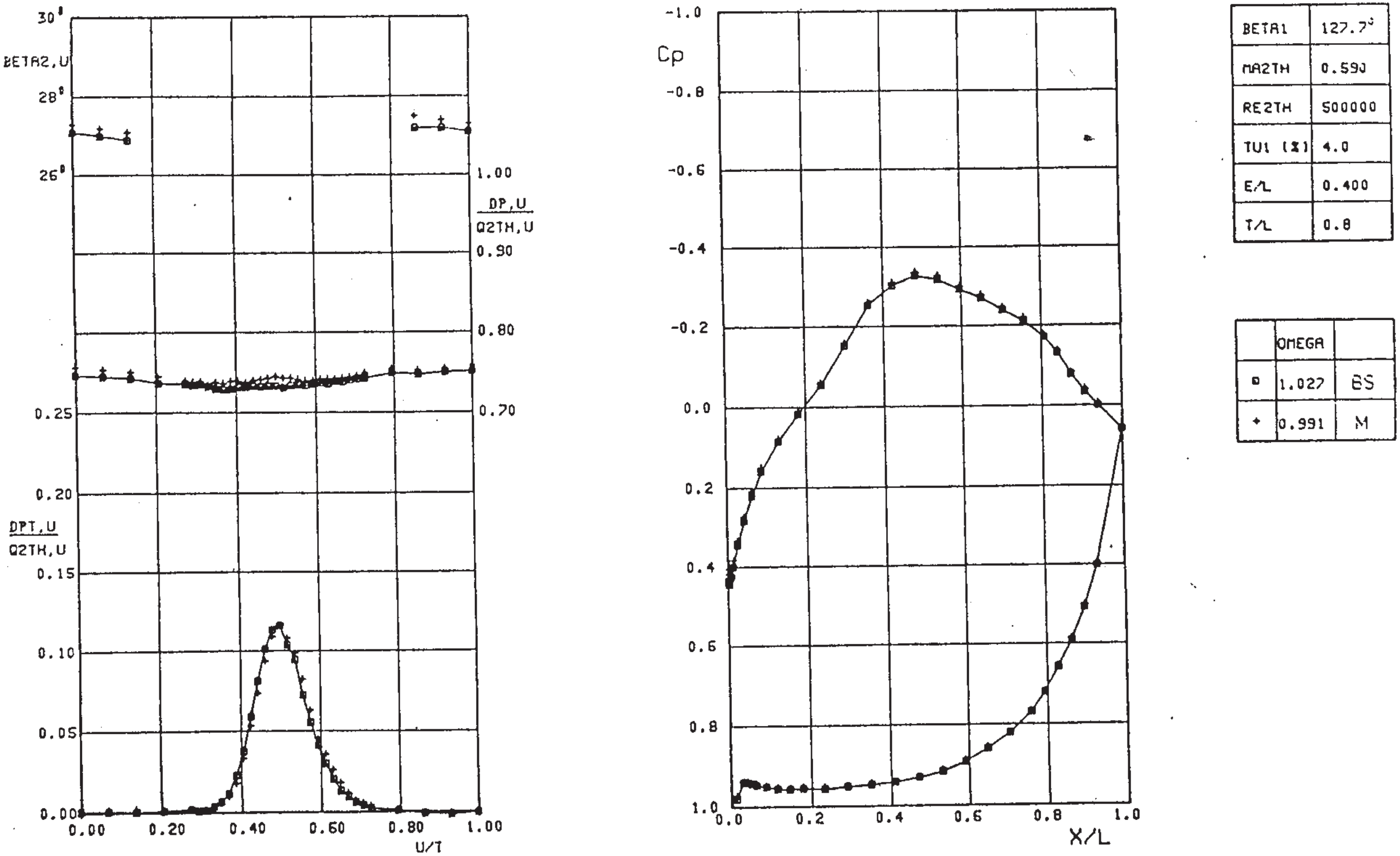


Fig. 2.3: Wake and profile pressure distributions of the turbine cascade T 106 at design point measured in Braunschweig (BS) and München (M)

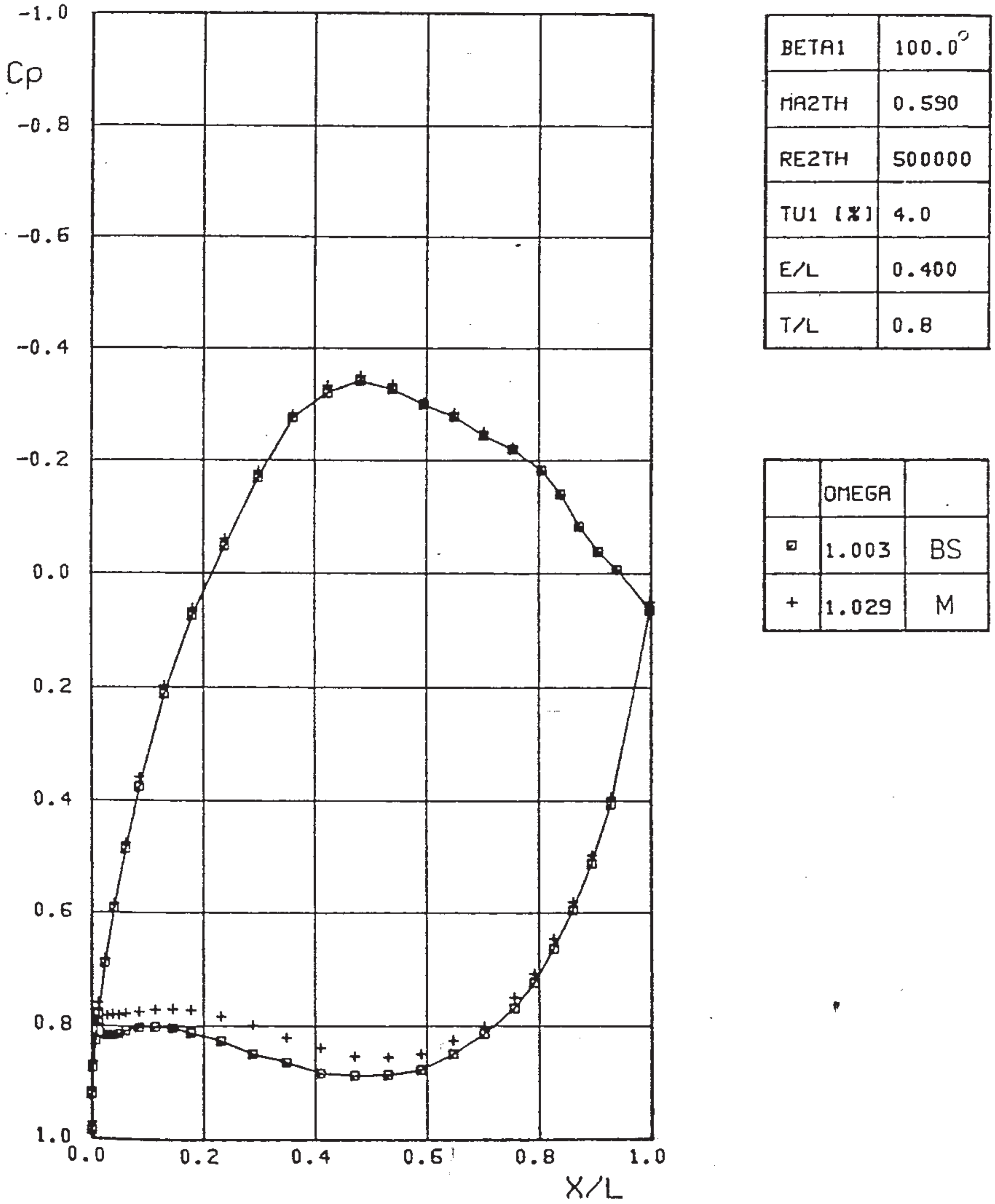


Fig. 2.4: Profile pressure distribution of the turbine cascade T 106 at an inlet angle β_1 = 100° measured in Braunschweig (BS) and München (M)

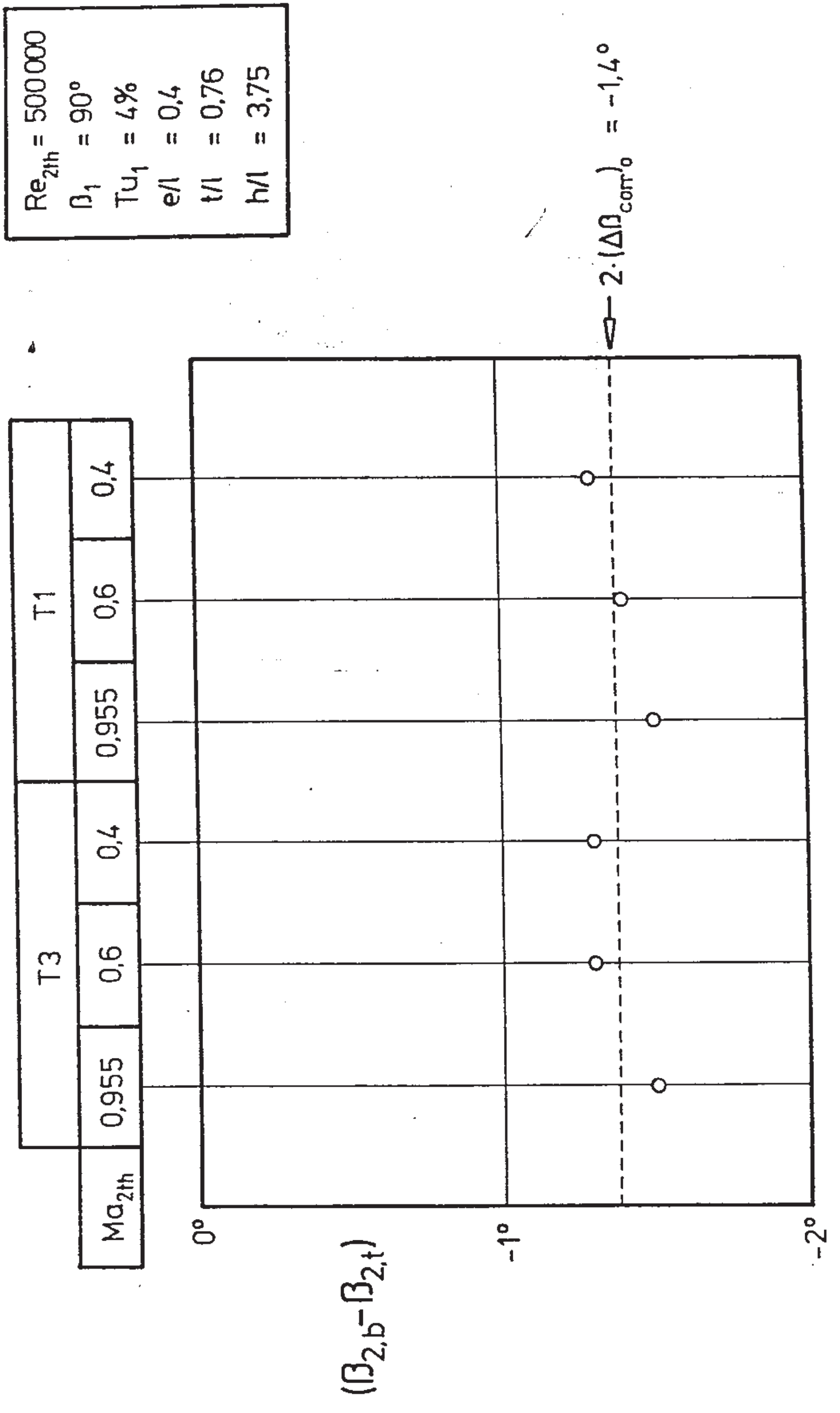


Fig. 2.5: Determination of the average exit angle deviation $\Delta\beta_{corr}$ measured with turbine cascades T1 and T3 with exit flow direction to the top (t) and to the bottom (b) of the vacuum tank

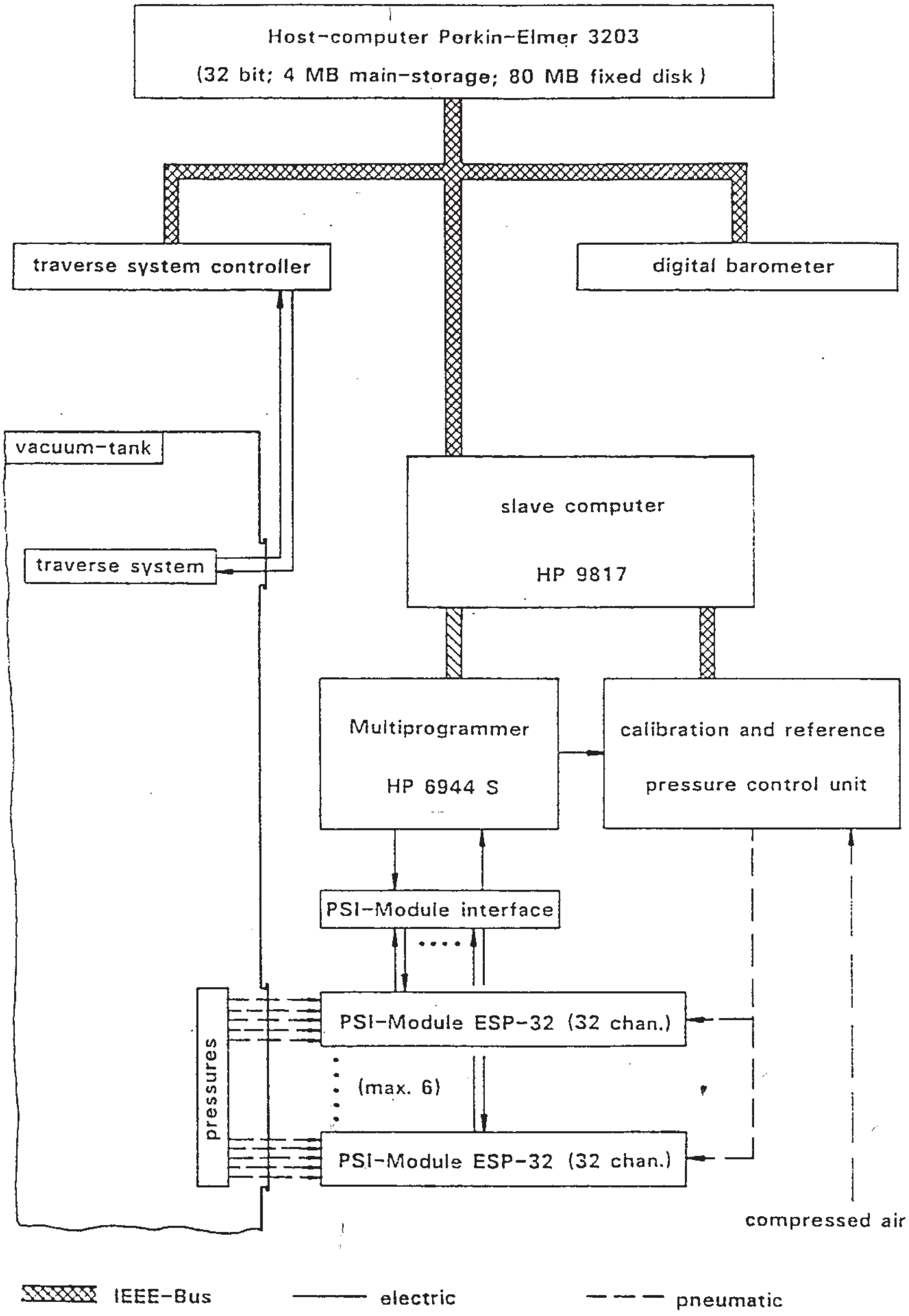
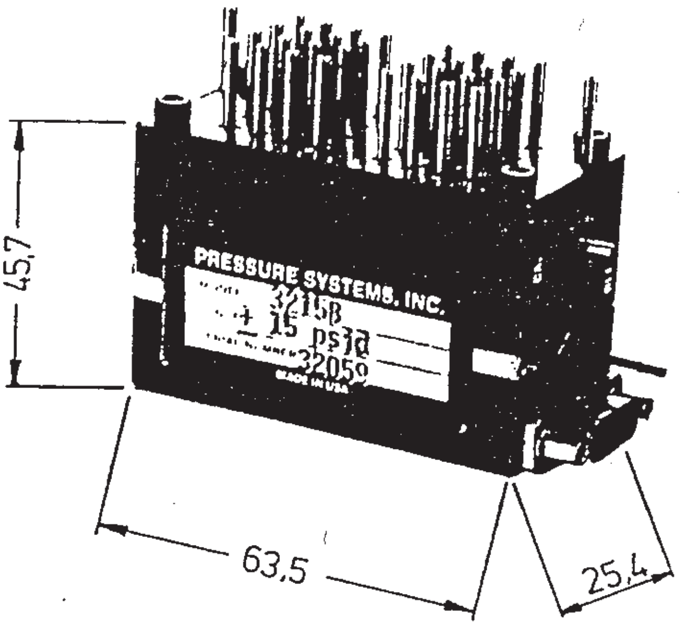


Fig. 3.1: Schematic view of the measurement and signal analysis system for wake and profile pressure distribution measurements



Features

- 32 piezoresistive pressure transducers (±15 psid) with common reference pressure
- built-in multiplexer (max. 20kHz) and amplifier
- accuracy 0.1% FS
- online calibration capability during measurements:

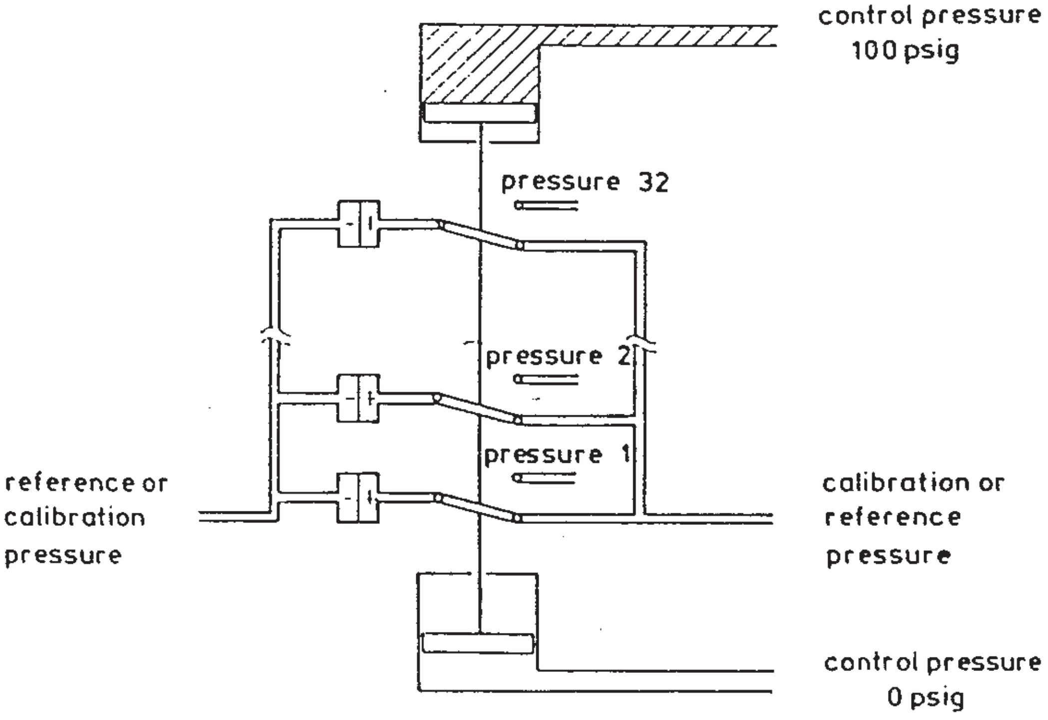


Fig. 3.2: Pressure transducer module PSI ESP 32

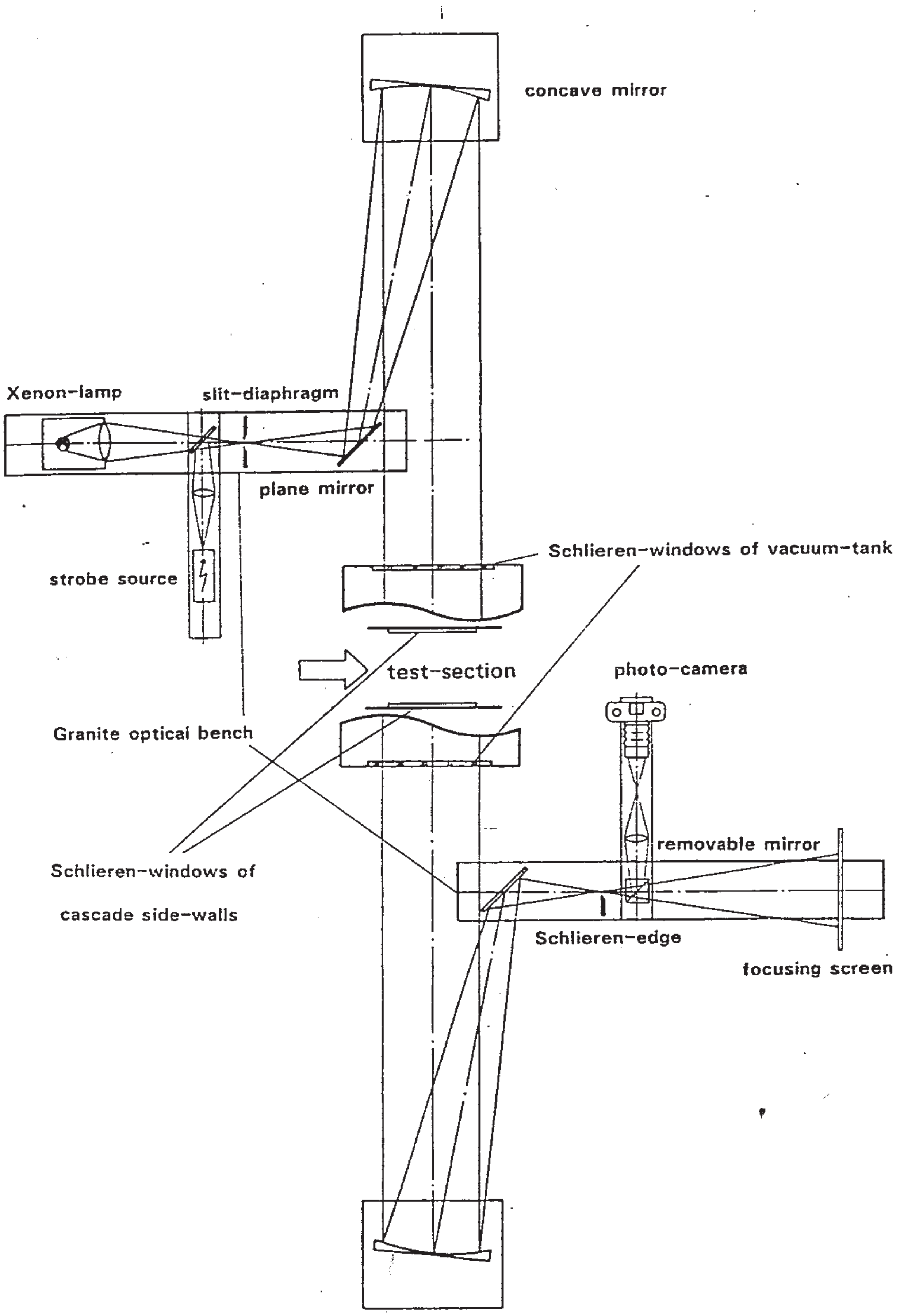


Fig. 3.3: Schematic view of the Schlieren-measurement system

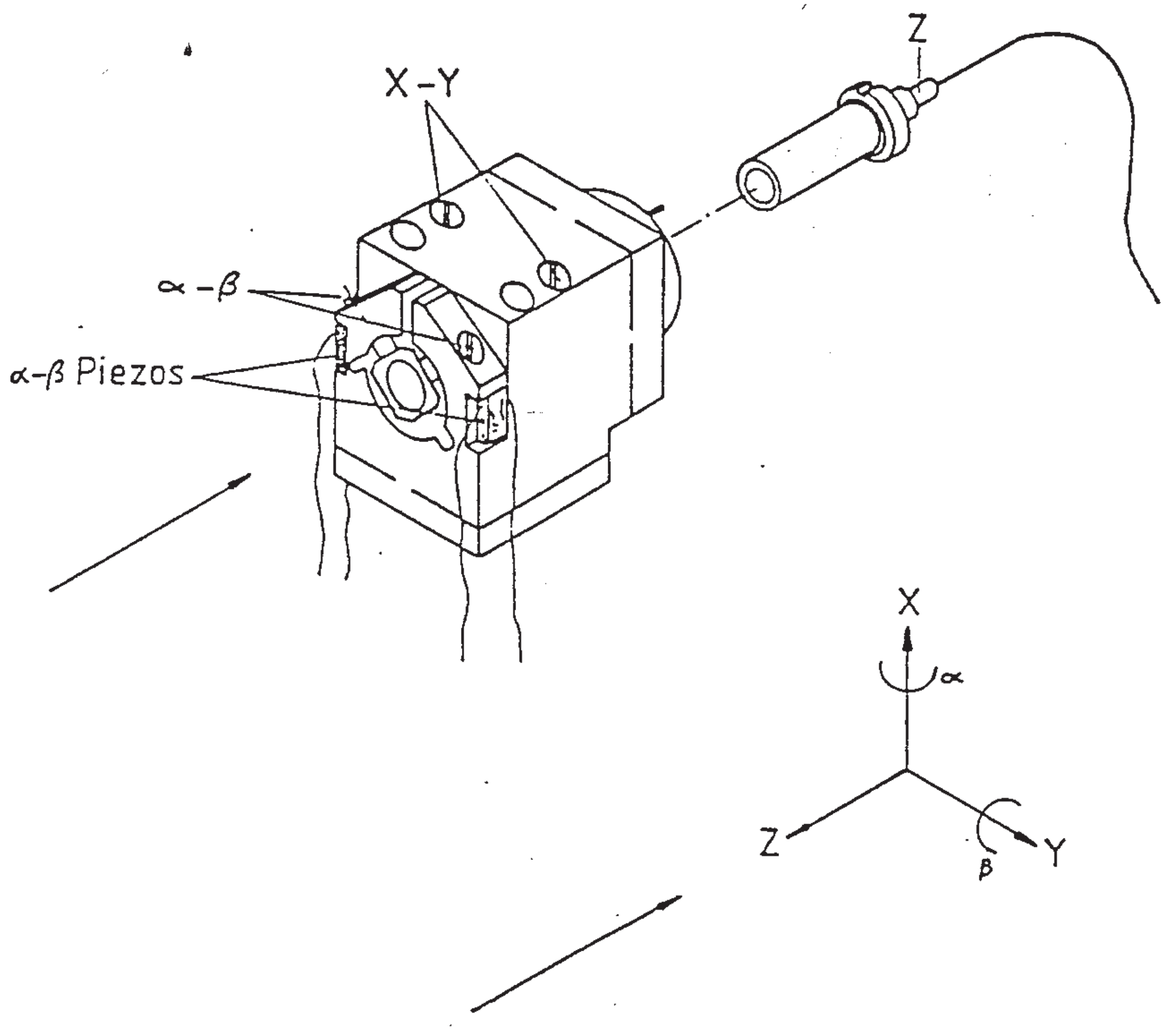


Fig. 3.4: Fiber optic coupler of the laser-two-focus velocimeter

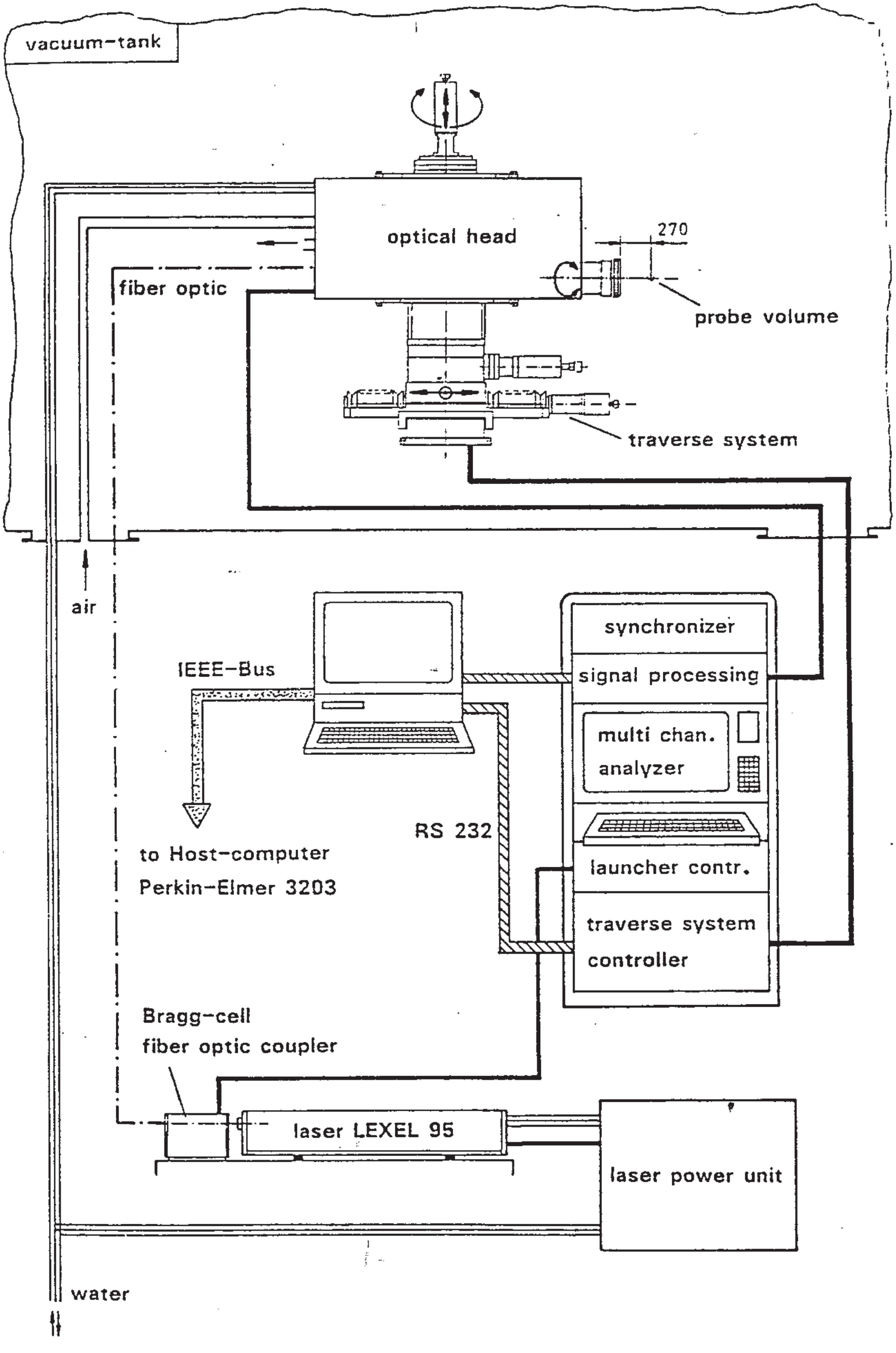


Fig. 3.5: Schematic view of the laser-two-focus measurement and signal analysis system

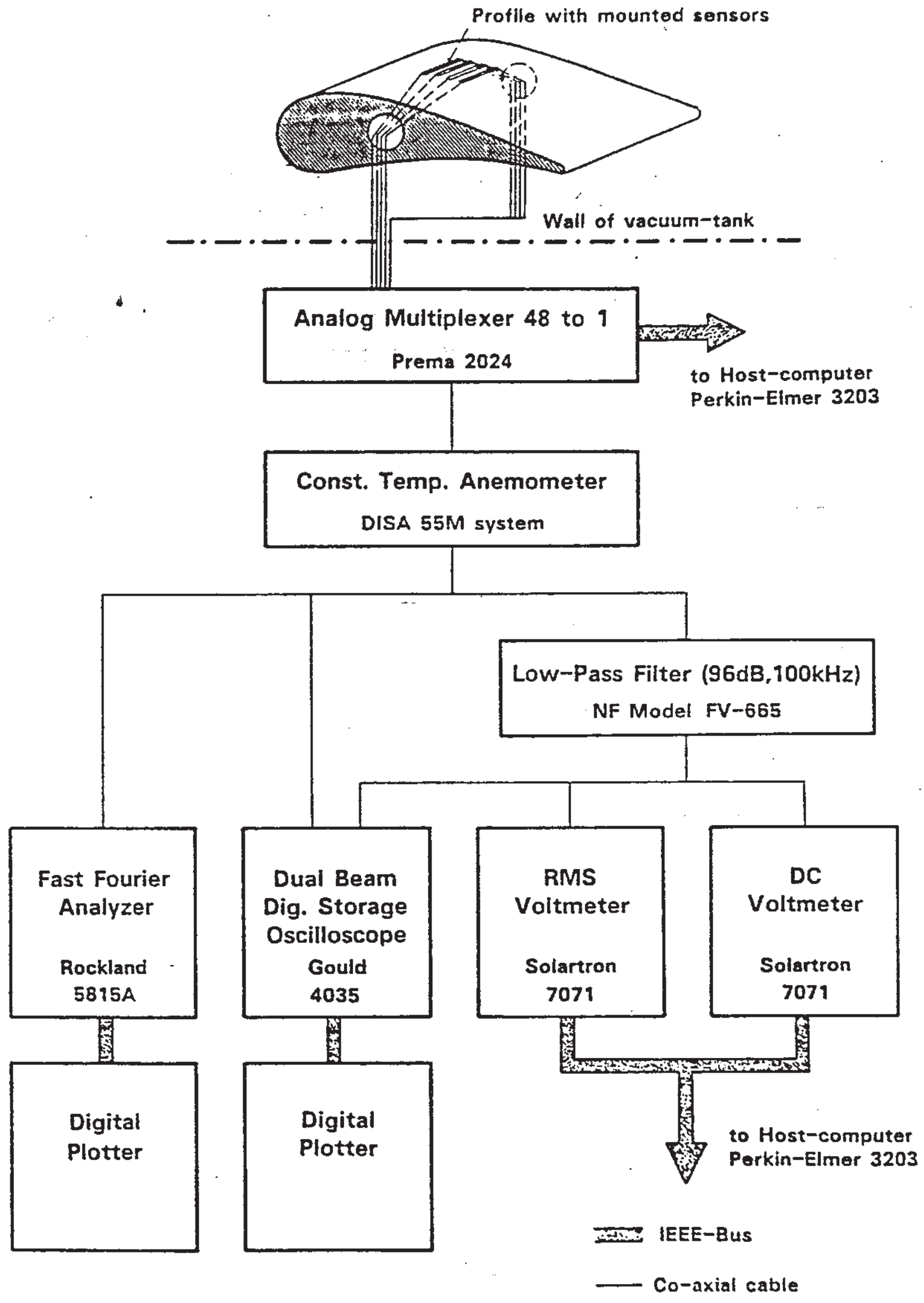
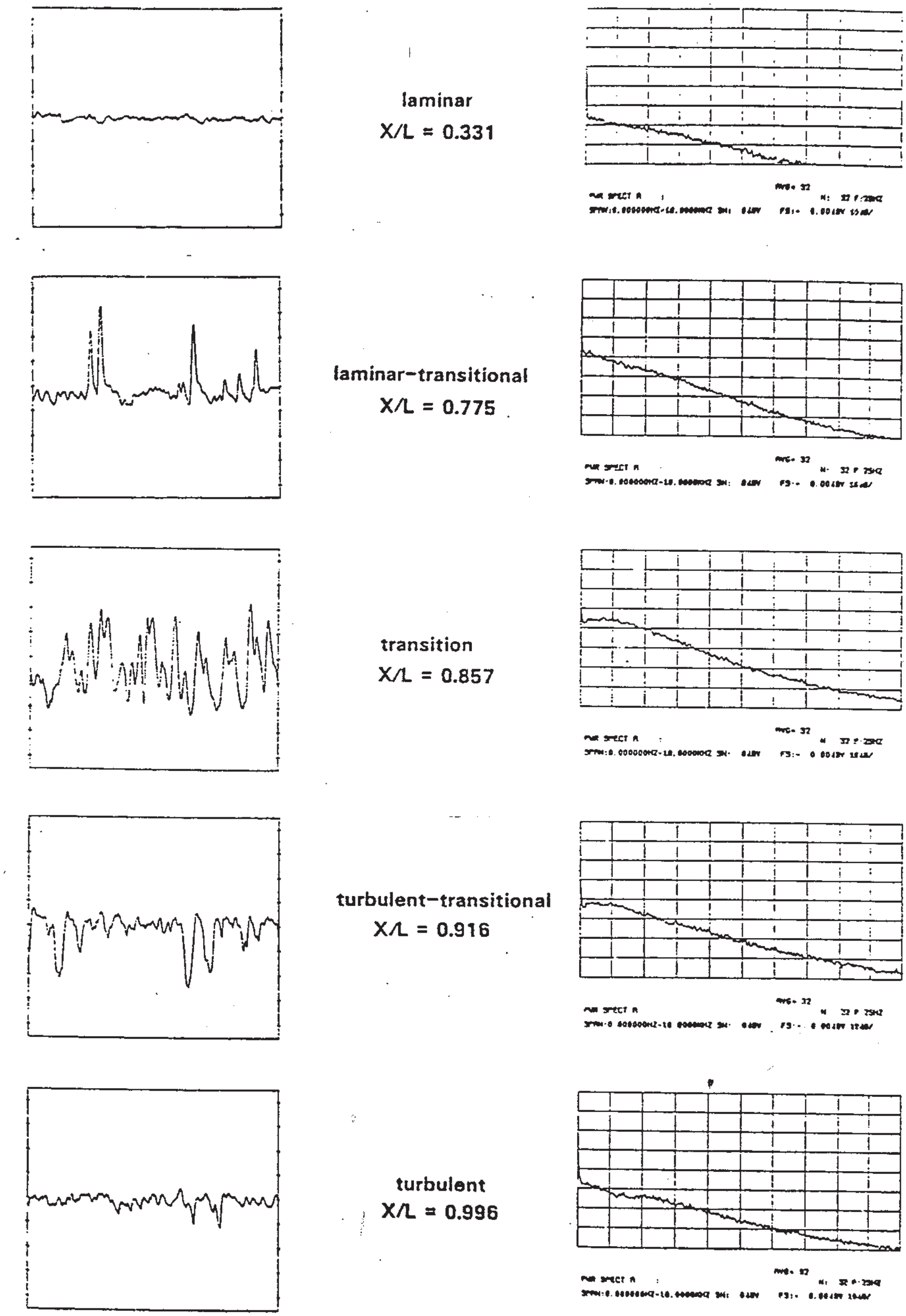


Fig. 3.6: Schematic view of the heated thin-film measurement and signal analysis system



laminar
X/L = 0.331

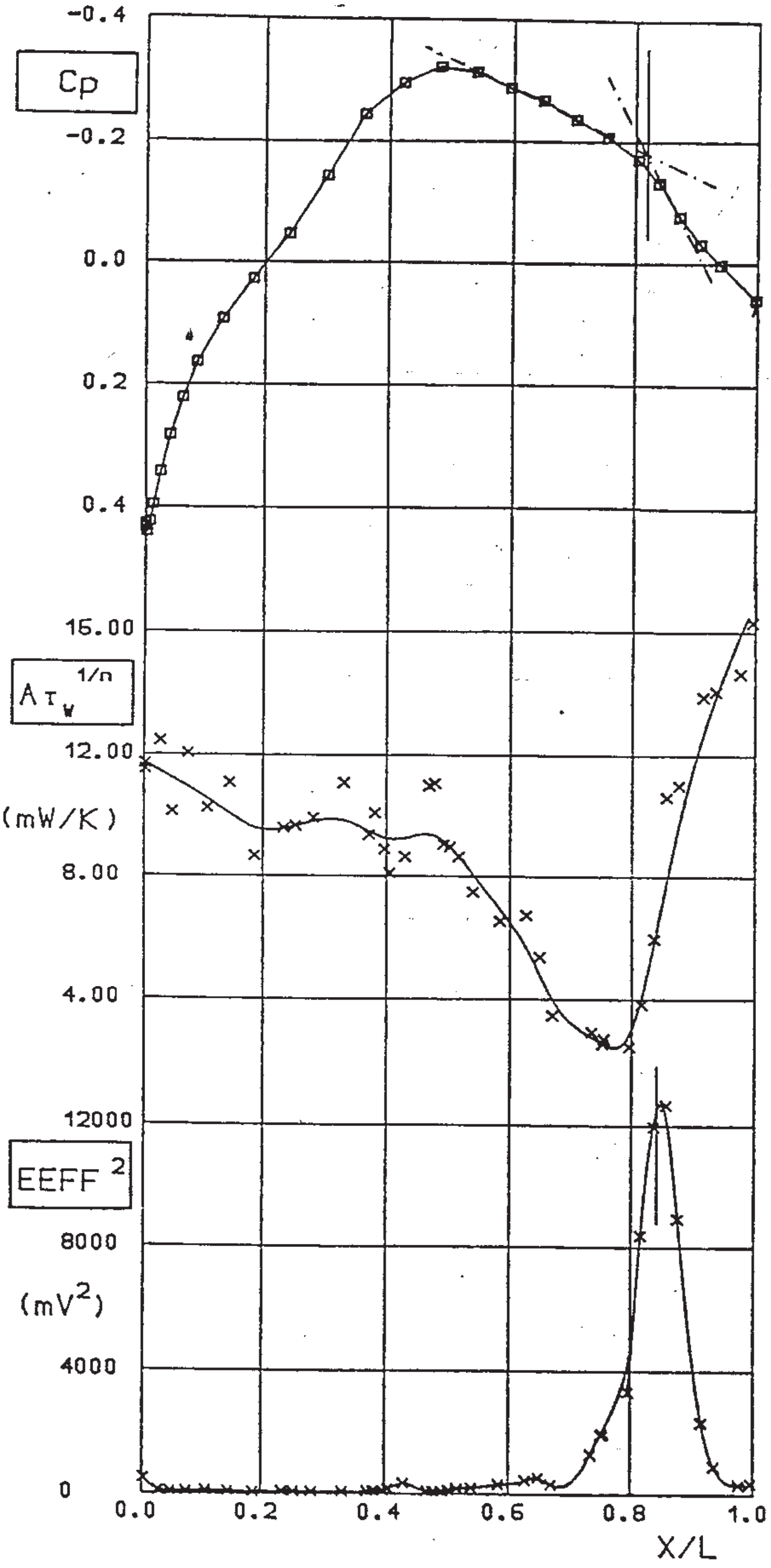
laminar-transitional
X/L = 0.775

transition
X/L = 0.857

turbulent-transitional
X/L = 0.916

turbulent
X/L = 0.996

Fig. 3.7: Scope and frequency analyzer plots of heated thin-film sensors corresponding to different flow characteristics of the boundary-layer



RE2TH	500000
MA2TH	0.59
TU1	5.5 %
BETA1	127.7 °
DELTAT	30 K
VERNR.	186

Fig. 3.8: Heat transfer rate results of heated thin-film sensors compared with profile pressure distribution measurements on the turbine cascade T106 at design point

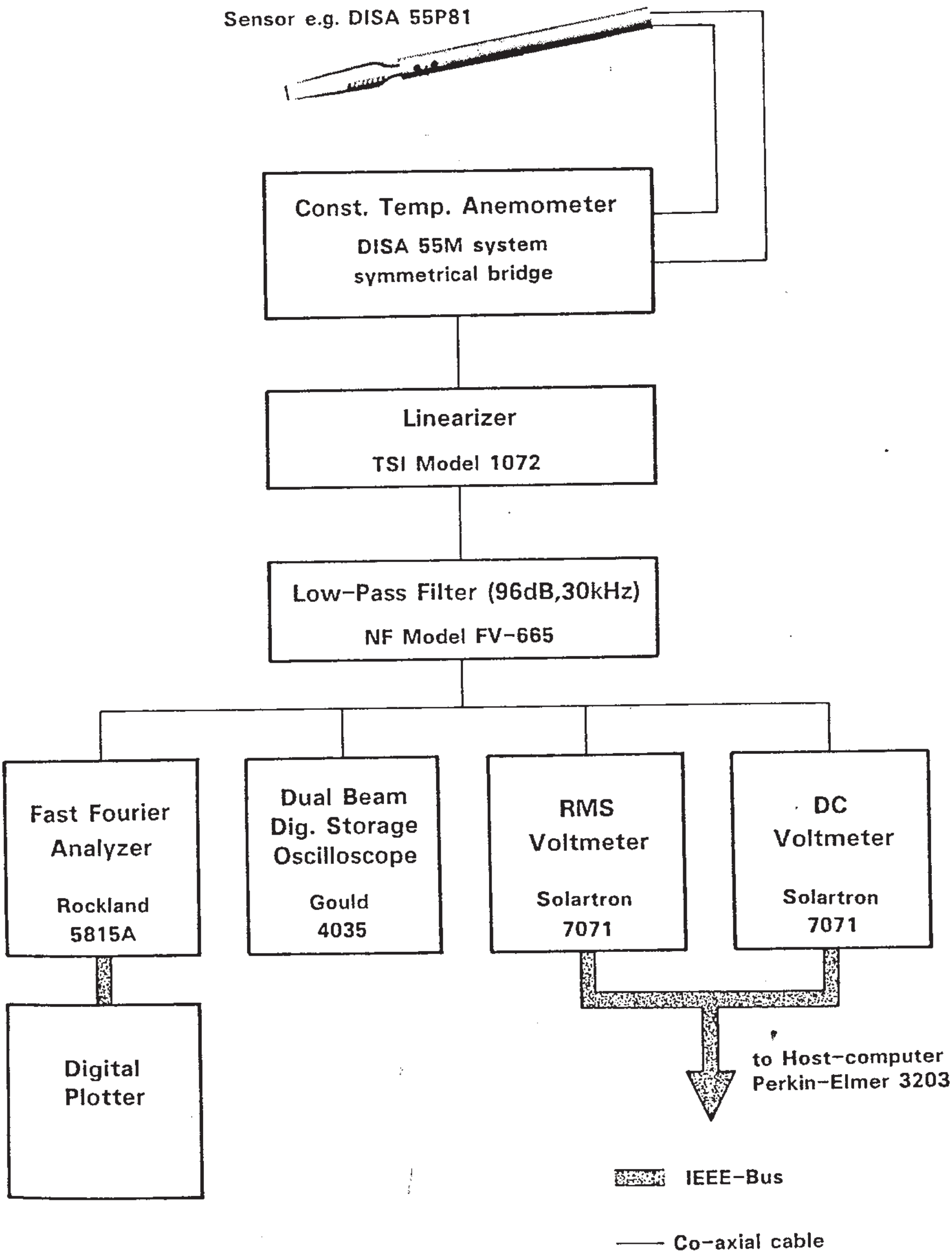


Fig. 3.9: Schematic view of the hot-wire measurement and signal analysis system