ULTRA FAST ELECTRON BEAM X-RAY COMPUTED TOMOGRAPHY FOR TWO-PHASE FLOW MEASUREMENT

F. Fischer[1], U. Hampel[1],

Institute of Safety Research, Forschungszentrum Dresden-Rossendorf e.V., POB 51 01 19, 01314 Dresden, Germany, F.Fischer@fzd.de

ABSTRACT

Electron beam X-ray CT is a new technique for a fast measurement of multiphase flows with frame rates of 1000 images per second and more. It gives, in principle, quantitatively accurate images of the flow at high spatial resolution and it is non-intrusive since moderately radiation absorbing vessel walls can be penetrated by X-rays. However, on the road to a technical realisation of such a technique within a computed tomography system many problems have to be solved. As a first prototype for scientific flow measurement studies we devised and built a fast scanned electron beam X-ray tomography scanner. The scanner consists of an electron beam unit that can be operated at up to 150 kV acceleration voltage and up to 65 mA electron beam current, with the required electron optics for beam adjustment, beam focussing and beam deflection unit and a fast circular CZT detector comprising 240 elements of 1.5 mm x 1.5 mm x 1.5 mm active pixel area. X-ray radiation is produced on a circular water cooled tungsten target The CT system achieves up to 7000 frames per second with a spatial resolution of 1 millimetre. First two-phase flow experiments have been carried out on gas-water flows in bubble columns. On the basis of these data we developed image processing algorithms which enable to extract information on bubble shapes, bubble size distributions and interfacial area density distribution. Further, a vertical test section made of titanium alloy has been installed at the TOPFLOW facility and will be used in the future to study the evolution of two-phase gas-water pipe flow at high pressures and temperatures.

Keywords: Two-phase flow, electron beam tomography, CFD code validation

1. INTRODUCTION

Two-phase flows are of primary importance in the understanding of thermal hydraulic phenomena in nuclear light water reactors. The qualification of CFD codes for the simulation of stationary and even transient two-phase flows in complex three dimensional geometries requires extending our knowledge toward the details of the flow structure under various thermal hydraulic conditions. At Forschungszentrum Dresden-Rossendorf the thermal hydraulic test facility TOPFLOW is currently extensively used to conduct two-phase flow experiments which aim at the disclosure of fine flow structure details in generic and also more complex geometries. Especially for upward adiabatic two-phase pipe flows in the bubbly to churn turbulent flow regimes valuable experimental data of the flow structure was generated in the past using the wire-mesh sensor technology. Wire mesh sensors have been extensively used for gas-liquid two-phase flow studies in the past. Their design and functional principle is described in detail elsewhere [1]. Basically, a wire mesh sensor is a set of thin electrode wires stretched across the pipe diameter in a mesh like fashion. Fast electrical conductance measurement between crossing wires enables recording cross-sectional phase distributions in the flow with temporal resolution in the range of 10.000 frames per second at about 2 mm spatial resolution. A known drawback of the wire mesh sensor is intrusiveness. The sensor changes the flow structure especially for low liquid velocities and consequently it cannot be applied in all scenarios of two-phase flow, especially if phase fraction measurement accuracy is required, as is the case for CFD code validation.
Consequently, we have recently extended our measurement technology for two-phase flow to high-speed X-ray tomography which offers non-intrusive flow measurement at a speed comparable to the wire-mesh sensor [2], [3], [4], [5]. X-ray CT as an imaging modality is highly advantageous due to its non-invasiveness and its ability to penetrate opaque wall materials. One essential disadvantage of classical CT systems is the requirement for a rotating object or source-detector setup. To measure multiphase flows in a flow velocity

range of up to 1 meter per second frame rates of up to 1000 frames per second are required. To achieve this, mechanically rotating parts are to be avoided. Scanned electron beam technology provides a mean to circumvent this problem. Instead of mechanical rotation of scanner components an electron beam is rapidly swept across an X-ray target using deflection coils. This technology has been introduced in medicine more than two decades ago were it is mainly used for cardiovascular diagnostics [6], [7]. However, medical systems with frame rates of about 20 fps are still too slow for technical flow diagnostic problems. For that reason we have developed a scanned electron beam X-ray apparatus which can today already perform cross-sectional imaging at high frame rates and will in the future be extended to other measurement features, such as multi-plane tomography, phase velocity measurement, higher scanning diameters and high energy X-rays. In this paper we introduce the scanner design, discuss major performance parameters along with an application example and show how this scanner will be applied to air-water and steam-water two-phase flow measurement in a vertical test section of the TOPFLOW facility.

2. SYSTEM DESIGN

The block scheme of the scanned electron beam X-ray CT system is shown in figure 1. Essential components are the electron beam generator, a metal target for X-ray generation and a fast multi-channel X-ray detector.

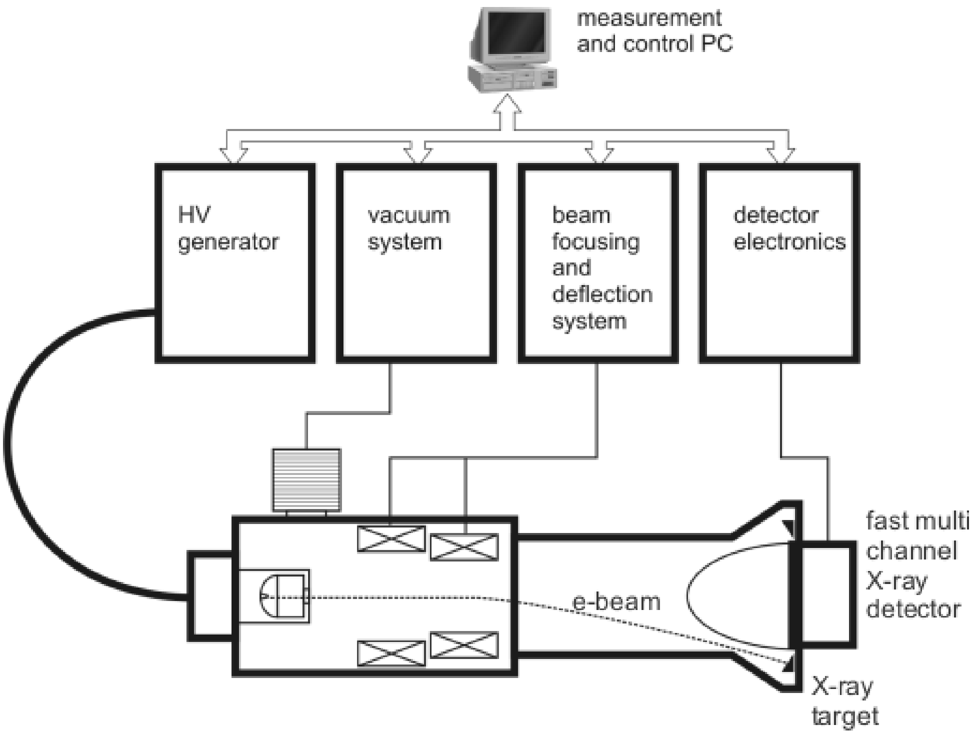

Fig. 1: *Block scheme of scanned electron beam X-ray CT.*

The electron gun produces an electron beam with maximum beam current of 65 mA at 150 kV acceleration voltage. The beam is focused on a tungsten target at the far end of the beam column. Focussing and centring is performed by separate beam optics. An x-y-deflection system consisting of deflection coils and associated fast high-current amplifiers periodically sweeps the beam on the target along a well defined path, thus producing a moving X-ray source of less than 1 mm diameter (Fig. 2). Maximum sweeping frequency is 10 kHz. A maximum sweeping range of ±15° with respect to the undeflected state in both directions is possible. For optimum electron beam generation the vacuum enclosure is kept at 1 Pa pressure by operation of a turbo molecular pump.
The far end of the electron beam column has been designed in a horse shoe shape and contains the X-ray metal target. We currently employ a semi-circular ring target of 240° opening angle and 250 mm diameter,

which is similar in shape to conventional electron beam tomography targets. Other targets, especially for multi-slice CT, are in preparation. The target is inclined at 30° to the beam axis. In this way it is for instance possible to perform scans on a vertical pipe that runs through the opening in the horse shoe scanner head (fig. 3). The current design enables imaging objects of up to 130 mm diameter. Target cooling is provided by means of a cooling water loop located at the top of the beam column. To easy beam positioning inside the vacuum chamber we provided electron catcher strips in the target region which are used for beam monitoring via time resolving charge detectors and additionally we installed a camera inside the beam column to visualise the focal path of the electron beam. The X-ray exit window is made of 0.7 mm thick aluminium.

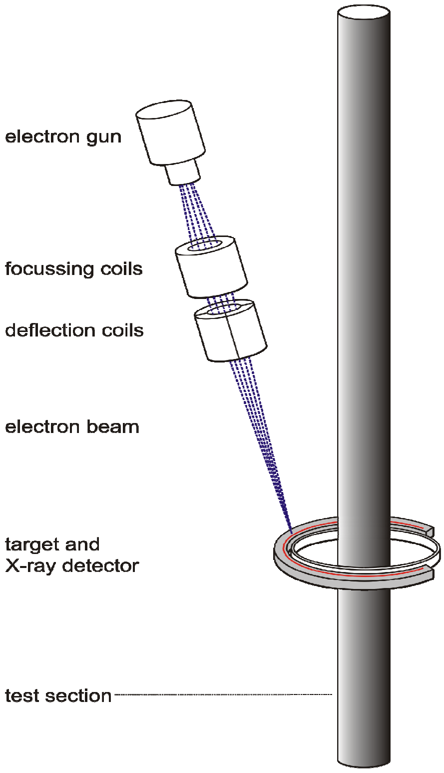

Fig.2: ***O****perating principle of the scanned electron beam X-ray tomograph.*

Fig.3: *Photography of the mounted apparatus at a vertical test section of FZD's TOPFLOW two-phase flow test facility*

The X-ray detector is arranged in a circular manner along the inner wall of the horse shoe enclosure in 360°. It has a slight axial offset of approximately 5 mm from the source path. It consists of 240 CZT detector elements, each of 1.5 mm x 1.5 mm x 1.5 mm size. The detector ring is made separable for easy removal and mounting about objects. The detector elements are operated in current mode with gain selectable amplifiers. This allows us to choose an optimum operating speed and integration time constant for the given imaging problem. The amplifiers are followed by 12 bit analog-to-digital converters which are controlled by a single microcontroller. Data from the converters are fed into a temporary data RAM of 4 GByte size. Maximum sampling rate of the detectors is 1 MSample/s at 500 kHz amplifier bandwidth and the electronics can operate up to 512 detectors in parallel at full 1 MHz sampling rate. The clock signal for data acquisition is generated by the detector controller and synchronised with the analog signal input from the deflection coil amplifier electronics. Communication between PC and detector electronics as well as the measurement data transfer is done via USB 2.0 interface (Fig. 4).

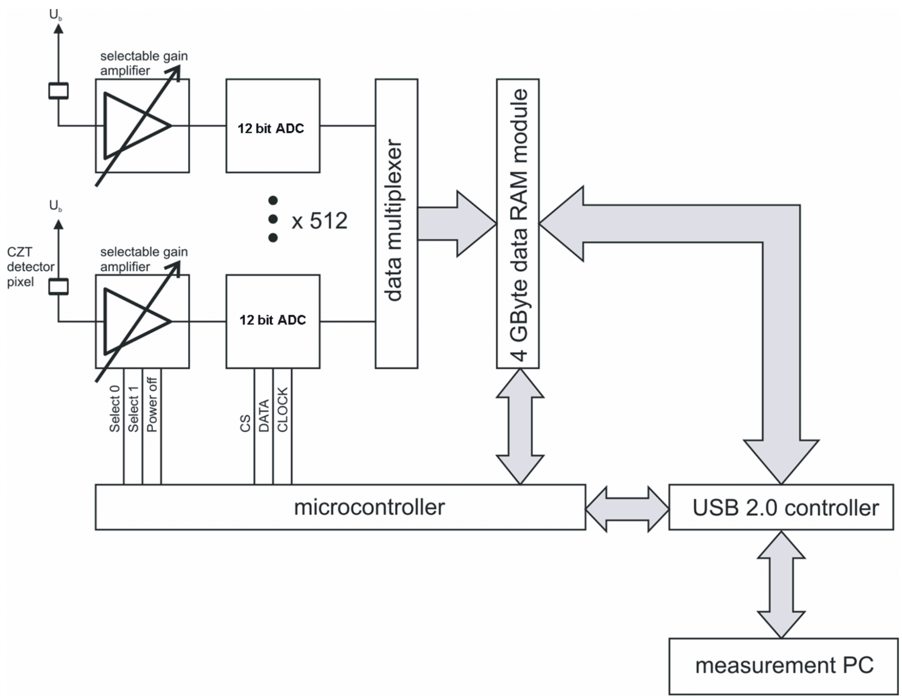

Fig.4: *Schematics of the fast X-ray detector electronics.*

The scanner is controlled by a 19” industrial PC that resides in an industrial control rack. This rack further includes the vacuum pump controller, focussing and deflection amplifiers and the high voltage control. The control software has been developed with LABVIEW and implements the following functions:

- Control of vacuum pump and vacuum monitoring via vacuum gauge,
- Control and monitoring of the high-voltage generator,
- Steering of the beam focusing and deflection system, both done by 16 bit 1 MSample/s digital-to-analog converter cards,
- Control and read-out of the X-ray detector.

3. DATA PROCESSING

Once a scan has been performed and data has been transferred to the PC the data is pre-processed and reconstructed according to the classical image reconstruction principles of CT [8]. The raw data is given by the binary detector readings, that is, 240 12bit integer values for each temporal sampling step of the detector. This data sequence is first broken into sets of size $N_D \times N_T$ where N_D=240 is the number of detectors and N_T the number of equidistant temporal points for a complete electron beam revolution. Next the data of each frame is mapped from the temporal domain into the angular domain of the target. That is, we calculate a projection data matrix of size $N_D \times N_S$ where N_S is the number of equidistantly distributed source positions on the target. Note, that this transformation is a comparatively complex nonlinear one which is necessary due to the fact that the source trajectory on the target is a cut of a skewed elliptical cone. Now the data can be resorted into a fan beam data set as for a conventional CT scanner. Thereby, we discard all data from source positions outside the valid angular scanning range of 240°. For the fan beam data of each frame the line integral X-ray attenuation values are calculated according to

$$E_{i,j} = -\log \frac{I_{i,j} - I_{i,j}^{(d)}}{I_{i,j}^{(0)} - I_{i,j}^{(d)}} \tag{1}$$

Here, I denotes X-ray intensity, *i* and *j* are the indices of detector and projection, superscript (d) denotes a previously acquired dark reference and (0) a previously acquired reference measurement with no object in the tomographic cross-section. Eventually the data is reconstructed by the fan-beam reconstruction algorithm. In our software implementation we reconstruct the data on a 128 x 128 pixel grid using a Hamming window smoothed ramp filter for restoring the image from the unfiltered backprojection. Data processing and image reconstruction takes about 2 s for one frame. Thereby the scanner allows us to scan the flow for as much as 10 s overall time with a temporal resolution of 1000 frames per second. Thus, the data is acquired at full speed and data processing needs to be performed in an offline mode after the scan.

4. SCANNER PERFORMANCE AND APPLICATION EXAMPLE

4.1. Scanner parameters

Spatial resolution within the reconstructed images has been determined from the edge of a scanned object as shown in fig. 5. The figure shows the modulation transfer function from a grey value profile along a horizontal line through one of the edges of the object. As a result we obtain a value for the spatial resolution of the scanner of 0.51 line pairs per millimetre at 10% MTF.

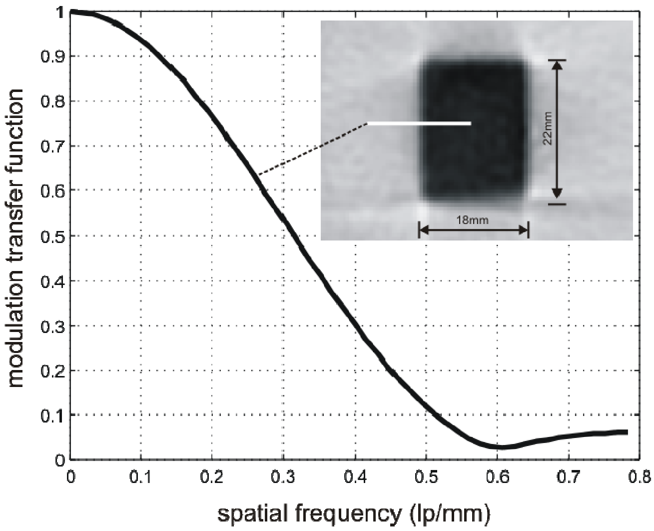

Fig.5: *Modulation transfer function obtained from a reconstructed object edge.*

Figure 6 shows results of a reconstruction of a different phantom containing four cylindrical absorbers of 8 mm diameter and different attenuation. They were scanned with 1 kHz frame rate and figure 6 bottom shows the corresponding time sequence of the grey values of selected pixels from each of the absorbers and a background pixel. From the plot we may obtain the temporal measurement uncertainty for a single pixel which is numerically summarized in Table 1. The measurement uncertainty for the short term variations comes mainly from the limited photon statistics in the 1 µs integration window of a single frame. For the case of discrimination of pure water (pixel number 2) from air (pixel number 1) we obtain a standard deviation of 3.3% relative to the mean attenuation difference between water and air. This shows a good discrimination capability of the tomographic scanner for the case of water-gas two-phase flow measurement.

Table 1: Mean and standard deviation of pixel values in Fig. 6.

Pixel number	Mean value	Standard deviation
1	1.3	0.49
2	10.4	0.34
3	21.8	0.37
4	32.8	0.45
5	40.2	0.43

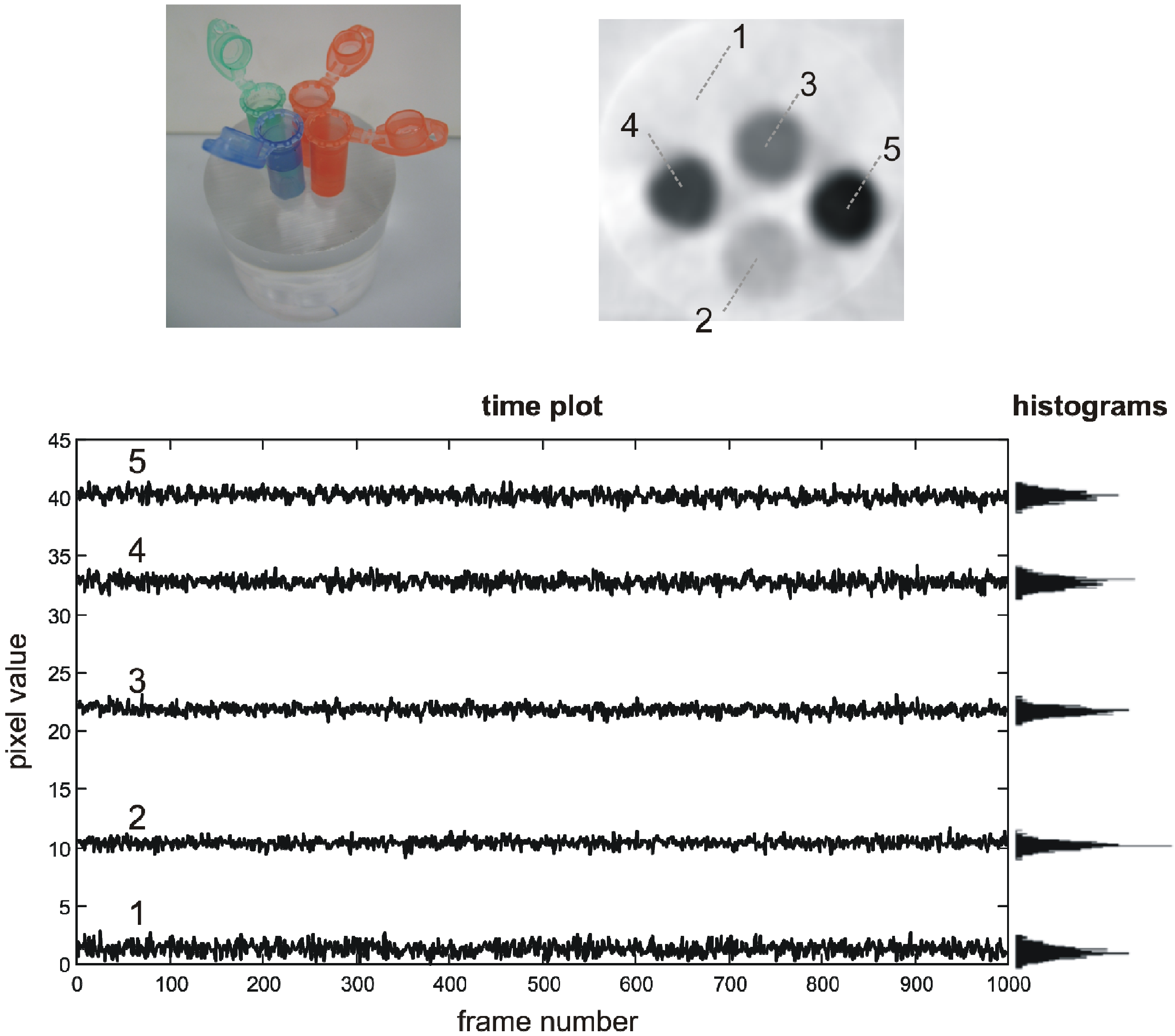

Fig. 6: *Image noise assessment: In the top the phantom with four tubes filled with four different substances along with a reconstructed slice image are shown. The bottom plot shows the temporal values of the central pixel of each absorber and one background pixel. The histograms at the right illustrate the spreading of the reconstructed attenuation coefficient.*

4.2 Stability of X-ray generator and detector system

The stability of the tomography system is determined by spatial stability of the electron beam (i. e. positioning accuracy on the target) and by the drift behaviour of beam generator and X-ray detector. The acceleration voltage fluctuation caused by electromagnetic influence is given by the manufacturer of the electron beam gun to 2% max. This leads to slight chromatic aberration of the beam and an error of positioning of the electron beam. For the smoothness of the electron beam current the ripple of the Wehnelt voltage is to be considered only, because the cathode is indirectly heated by electron bombardment. The Wehnelt ripple is about 0.3%. Together with the 2% ripple of acceleration voltage the positioning error is about 1.5 millimeters maximum on the target. Long term stability of the specifications is given to 1% within 8 hrs. The temperature drift of the X-ray detector is about 3% within 1 hour. Because of the very high measuring speed all required data sets (including reference) were recorded within a few minutes and therefore these drifts are out of scope for data acquisition. Concerning the absence of space for a collimator between the CdZnTe crystals in the tomograph´s head there is an error due to the incidence of scattered X-rays which is estimated to 5%.

4.3 Two-phase flow application example

An essential application example is a two-phase flow in a bubble column like vessel. The column we used was of 60 mm inner diameter and 500 mm height and made of Perspex. Gas was injected at different flow rates from the bottom by a single injector needle in stagnant water, and the measurement was performed 150 mm above the bottom of the vessel. Fig. 7 shows the extracted gas-liquid interfacial area in an extra three-dimensional volume plot of the column for three flow rates. The scan was performed at 5000 frames per second for 0.5 s scan duration. As can be seen all bubbles are well resolved and even thin liquid film between the single bubbles can be recognized.

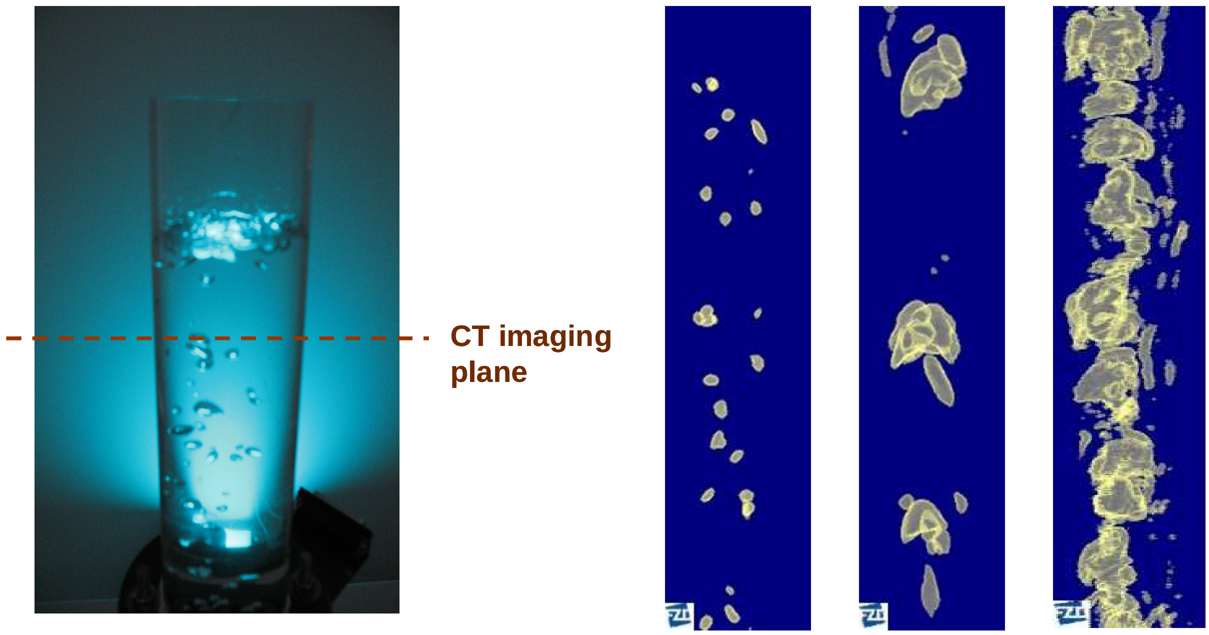

***Fig.** 7: Photography of bubble column and three-dimensional phase boundary plot of the gas phase in the bubble column for three different flow rates. The sequence has been synthesized from 500 slice images. Note that the vertical coordinate has the dimension of time.*

5. TWO-PHASE FLOW MEASUREMENTS AT THE TOPFLOW FACILITY

For the future two-phase gas-liquid flow measurements at the TOPFLOW facility (Transient Two-Phase Flow Test Facility) at FZD are planned. Targets are air-water and steam-water two-phase flows in a vertical pipe of DN50. The objective of these studies is the investigation of the flow evolution for different gas and liquid superficial velocities and a comparison of steam-water with air-water flows. The new X-ray tomography scanner now for the first time enables to perform a quasi-continuous axial measurement of phase fraction distributions with no intrusion and corresponding flow disturbance. To perform measurements with the scanner a vertical manipulator has been erected around the test section, which can lift the scanner into any required measurement position along the 4.2 m lengths of the pipe. The manipulator includes an elevating system driven by a stepper motor, and a mounting bracket to hold the CT-scanner in position (Fig. 8). The elevator is 1.5 m x 1.5 m wide and 6 m tall. The sliding carriage can be moved from position 0.5 m to position 4.5 m. It reaches a vertical translation velocity of 0.5 meter per second maximum. For radiation protection a casing made of 6 millimetres lead walls is mounted around the scanner. To balance the resulting heavy mass a counterweight is mounted on the elevator.
The test section is made of titanium alloy with 1.5 mm wall thickness, which is sufficient to withstand the nominal maximum pressure of 7 MPa inside the test section during steam experiments. At the bottom a multi-hole gas injection device is installed which enables homogeneous injection of small gas bubbles across the cross-section of the pipe. The gas injection device is a complex weldment made of stainless steel. It comprises 40 cannulae which are feed with gas from several ring chambers (Fig.9). The ring chambers can be activated separately to adjust the amount of gas bubble rate. In between the ring shaped gas chambers the water can flow continuously. Thus we get a well rectified, homogenous gas-water flow whose flow rate can be varied. Downstream the injector the flow will develop into its characteristic flow regime, which may be bubbly, churn, slug or annular. The X-ray tomography measurement begins directly at gas injection level. By moving the CT-scanner vertically along the pipe and scanning at arbitrarily selected levels we get complete data sets of the developing flow regime. For data processing additional software has been implemented, which enables segmentation of gas bubbles and measurement of volume and equivalent diameter. The statistical bubble data will then be compacted to radial gas fraction profiles which disclose the action of non-drag bubble forces and their role within the flow structure development. These data will in the future further be used to develop and improve models for bubble force balances in bubble and churn flow and help to validate two-phase flow CFD code predictions.

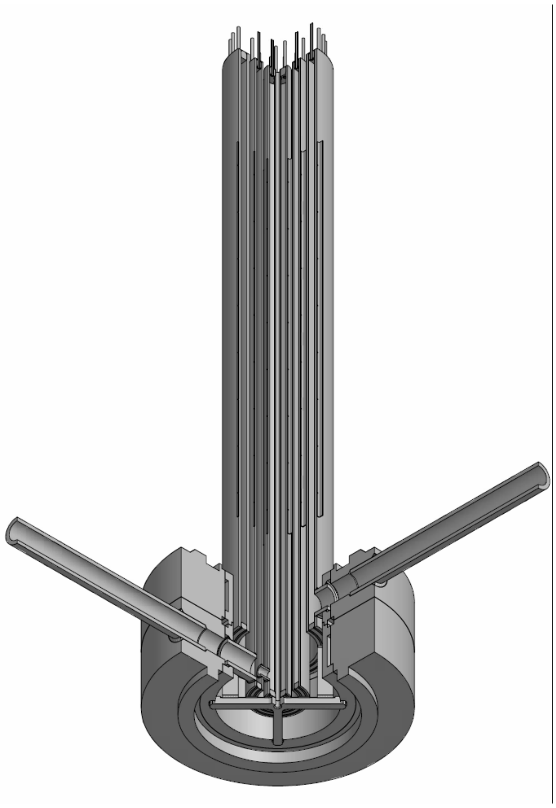

Fig.8: *Photography of the elevator system with CT scanner in lower position. (lead casing removed).*

Fig.9: *CAD drawing of multi-hole gas injection device.*

6. CONCLUSION

An ultra fast electron beam X-ray CT scanner for multiphase flow measurement applications has been designed, built and tested. The scanner comprises an electron beam generator with 150 kV / 10 kW high voltage supply, beam focussing, centring and deflection system, a semicircular X-ray production target made of tungsten alloy, and a 240 element CZT X-ray detector with fast data read-out. In scanning mode the beam is circularly guided across the target to produce a rapidly moving X-ray spot. The detector has a sampling rate of up to 1 MSample/s. After proper dark and reference calibration the data is processed by standard computed tomography algorithms based on the filtered backprojection technique to produce time series of cross-sectional images. The maximum frame rate of the scanner is so far at about 7 kHz, limited by the capability of the deflection coil amplifiers to adjust the required elliptical beam deflection pattern. The spatial resolution in the images has been determined as 0.51 lp/mm at 10% MTF. Further, the noise floor in the images is about 3% with respect to the mean attenuation coefficient of water. First scans on a water-gas two-phase flow have proven the functional principle of the scanner.

7. REFERENCES

[1] Prasser H-M, Böttger A and Zschau J 1998 "A new electrode mesh tomograph for gas–liquid flows" Flow Meas. Instrum. 9 111–9

[2] HAMPEL, U. et al., (2005), "Ultrafast X-ray Computed Tomography with a Linearly Scanned Electron Beam Source, Flow Measurement and Instrumentation" *16*, pp. 65-72, 2005

[3] SPECK, M. et al., (2005), "A limited-angle CT approach for a fast scanned electron-beam X-ray tomography with application to multi-phase flow measurements", Proceedings of the 4th World Congress on Industrial Process Tomography, Aizu, Japan, Sept. 2005, pp. 681-686, 2005.

[4] Bieberle, M.; Fischer, F.; Schleicher, E.; Koch, D.; Aktay, K. S. D. C.; Menz, H.-J.; Mayer, H.-G.; Hampel, U., "Ultra fast limited-angle type X-ray tomography", Applied Physics Letters 91(2007), 123516

[5] Bieberle M, and Hampel U 2007, "Evaluation of a limited angle scanned electron beam x-ray CT approach for two-phase pipe flows", Measurement Science and Technology 17(2006), 2057-2065 .

[6] BOYD, D P, Lipton M J 1983, "Cardiac computed tomography", Proc. IEEE 71 298-307.

[7] Gould R G 1992, "Principles of Ultra Fast Computed Tomography", in Stanford W, and Rumberger JA, "Ultrafast Computed Tomography in Cardiac Imaging: Principles and Practice", Mount Kisco, NY, Futura Publishing Co., Inc.

[8] KAK A., SLANEY M., "Principles of Computerized Tomographic Imaging", IEEE Press, (New York, 1988).