Development of micro-tomography system:
Design, fabrication and test

FINAL REPORT

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Summary

A non-destructive, powerful analysis of all safety relevant devices inside the highly activated test cell is urgently needed. Due to its penetration ability and contrast mechanism, the X-ray microtomography is the only known tool that could meet these requirements. This technique has the ability of monitoring voids, micro-cracks and flaws in activated and completely assembled rigs, test modules and the IFMIF Li-target back-wall. Consistent with the task objectives a cone-beam X-ray microtomographic system has been designed, fabricated and tested at the National Institute for Laser, Plasma and Radiation Physics (NILPRP), Bucharest-Magurele, Romania. The system consists of an open type microfocus X-ray source, a 3D micrometric translation and rotation samples manipulator and a 2-D X-ray detection system based on large area image intensifier and fast-scan CCD. The selection of optimum tomographic configuration and components is based on test measurements of miniaturized sample mock-ups carried out on existent tomographs as well as on fully 3-D Monte Carlo simulations of X-ray generation and transport. The 3-D tomographic reconstructions are obtained by our highly optimized computer code based on a modified Feldkamp algorithm. The new developed tomography system will allow us to provide the fusion materials community with a unique instrument for NDT inspection of individual miniaturized samples as well as for verification of irradiation capsules integrity. The micro-radiography analysis is guaranteed for feature recognition down to 1 micron. Currently, in tomography measurements with moderate magnification (approx 50) we assess as defect detectability a limit around 10 microns. As we have the ability to work with maximum magnifications over 1000 one can estimate that the defect detectability limit can be lowered to few microns. In addition, we proved that beam hardening artifacts are reduced by a correction method based on X-ray spectrum filtering and the linearization of the transmission curve. Also, we introduced a segmentation procedure for accurate geometrical measurements by micro-tomography. A consistent data base of the 3-D image reconstructions of the miniaturized samples in different development and testing phases was designed and implemented. In the process of using this facility for extensive NDT inspection of fusion materials miniaturized samples the main goal is to establish the reference design for transmission micro-tomography system for IFMIF environment conditions. An effort will also be made for development of new methods to cope with the challenging problem of beam hardening in high density materials. Fully 3D Monte Carlo radiation transport simulations combined with validation experiments represent our main tools in approaching these problems. In addition new inspection configurations will be investigated in order to visualise irradiation capsules integrity. During the irradiation campaigns in IFMIF, one produces highly radioactive miniaturized samples and capsules. During the year 2003 activity is launched for the elaboration of a technical concept of an emission tomography system for the examination of the structural integrity of activated and completely assembled rigs, test modules and Li-target back-wall of the IFMIF.
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References
1. Brief task description

A non-destructive, powerful analysis of all safety relevant devices inside the highly activated test cell is urgently needed. Due to its penetration ability and contrast mechanism, the X-ray microtomography is the only known tool that could meet these requirements. This technique has the ability of monitoring voids, micro-cracks and flaws in activated and completely assembled rigs, test modules and the Li-target back-wall.

Main goal of the current subtask is to provide a universal tool for the non-destructive analysis of fusion material samples (both structural and tritium breeders) before and after various tests, including irradiation. A short list of possible applications includes: monitorization of geometry and density variations, micro-cracks development by mechanical/thermal cycling, permeability and pore network connectivity in porous materials, microstructure of various components, welding capabilities of irradiated materials, visualization of surface deformations (blistering and flaking) induced by ion implant, high magnification microradiography for in-situ analysis of fusion material samples under mechanical and/or thermal tests.

Consistent with the task objectives a cone-beam X-ray microtomographic system has been designed, fabricated and tested at the National Institute for Laser, Plasma and Radiation Physics (NILPRP), Bucharest-Magurele, Romania. The system consists of an open type microfocus X-ray source, a 3D micrometric translation and rotation samples manipulator and a 2-D X-ray detection system based on large area image intensifier and fast-scan CCD. The selection of optimum tomographic configuration and components is based on test measurements of miniaturized sample mock-ups carried out on existent tomographs as well as on fully 3-D Monte Carlo simulations of X-ray generation and transport. Currently, the system is under commissioning phase. Next planned is extensive NDT inspection of fusion materials miniaturized samples using this transmission microtomography system in order to establish the reference design for micro-tomography system for IFMIF environment conditions.

2. Principle of transmission X-ray tomography

Computed tomography is widely used in the medical community and is receiving increased attention from industrial users including electronics, aviation, advanced materials research, casting and other manufacturing. Computed tomography systems are usually configured to take many views of the object in order to build a 3-D model of its internal structure. 2-D slices through this volume can be viewed as images, or the 3-D volume may be rendered, sliced, thresholded and measured directly. Amplitudes of the volume elements (or voxels) are proportional to the X-ray linear attenuation of the material at that position and are therefore dependent only on material properties and not on the shape of the object as in case of plain radiography.

Figure 1: Fan beam (left) versus cone beam (right) tomography configurations
The principle of most common transmission tomography configurations is depicted in figure 1. Traditionally, volumetric image reconstruction is achieved through scanning a series of cross-sections (slices) with a fan-shaped X-ray beam, and by stacking these slices. Recently, with the introduction of planar detectors, computed tomography began a transition from fan-beam to cone-beam geometry. In cone-beam geometry the entire object is irradiated with a point-shaped X-ray source, and the radiation attenuation is measured on a detector plane behind the object. The primary advantages of cone-beam geometry include reduced data acquisition time, improved image resolution, and optimised photon utilization.

3. Tomographic test measurements and design considerations

The X-ray microtomography is the only known tool that could meet IFMIF relevant requirements of monitoring voids, micro-cracks and flaws in activated and completely assembled rigs, test modules and the Li-target backwall.

The microtomographic systems have to fulfill rather difficult design constraints such as:

- high space resolution;
- wide range of material densities and attenuation coefficients;
- capably to work out limited access angle problems.

According to Bio-Imaging Research, world leader manufacturer of tomographic facilities, current industrial CT systems cost from 400,000 USD to over 2 million USD. While the commercial offers are very nice general-purpose instruments they might not satisfactorily address the main challenges of the microtomography analysis of the fusion material samples i.e. the intense beam hardening effects associated with high-density materials samples. Beam hardening artifact consists of an elevated density displayed on the perimeter of a uniform density probe and a corresponding density depression in the probe’s core region. It is caused by the polychromatic structure of the energy spectrum of the X-ray generators.

Since our total budget was slightly higher than the half of the minimum sum quoted above we had to consider to optimize the compact type, low energy (low power) microtomographic facility.

The evaluation of optimum tomographic configuration suitable for IFMIF test cell was carried out by test measurements on existing tomographs and through 3D Monte Carlo simulations of X-ray generation and transport. Based on these measurements we have drawn important conclusions for the subsequent design works.

According to the main needs of fusion material community we considered at the extremes of the range of material densities and attenuation coefficients two main types of samples: low density materials as ceramic and light metallic alloys and high-density metallic. In the later category most representative are steel samples.

3.1 Test measurements on a compact microtomographic facility

In the picture presented in figure 2 one shows the experimental setup and typical working conditions for a microtomographic facility with low energy (low power) X-ray source.
Figure 2: Compact microtomography facility - experimental set-up and operating parameters

The main characteristics of the principal components of the facility are listed in Table 1.

Table 1: Main characteristics of a compact microtomographic facility

<table>
<thead>
<tr>
<th>X-ray source</th>
<th>Manipulator</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model: Kevex, PXS5-925EA</td>
<td>Model: (Sigma Koki, Japan)</td>
<td>Linear Sensor (Hamamatsu Photonics Ltd. Co.)</td>
</tr>
<tr>
<td>Max. Voltage 90kV</td>
<td>Detector: 1 Z-axis</td>
<td>MOS Linear Image Sensor S3901-1024FX</td>
</tr>
<tr>
<td>Max. Current 90 microA</td>
<td>Sample Stage: 1 X, 1 Y, 1 Rot.</td>
<td>- 50 micro meter pitch,</td>
</tr>
<tr>
<td>Max. Power 8 watts</td>
<td>Source: 1 Z-axis</td>
<td>- pixel height 2.5mm</td>
</tr>
<tr>
<td>Window: Be</td>
<td>Steps 2micro meter/pulse for X, Y, Z stages</td>
<td>Controller Driver C7615</td>
</tr>
<tr>
<td>Focus Spot: &lt;7.0 micro meter</td>
<td>0.006deg./pulse for Rotation stage.</td>
<td>Power Supply C2892</td>
</tr>
<tr>
<td>Cooling: Air</td>
<td>Precision: X, Y, Z = 5 micro-meter, Rotation = 0.01deg.</td>
<td>Data Processing Unit C2890</td>
</tr>
<tr>
<td></td>
<td>Stroke: 50 and 100mm</td>
<td>- 12 bit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interface Board M7089</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- ISA bus, DOS/V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slit: 200 micro-meter</td>
</tr>
</tbody>
</table>
Due to rather insufficient X-ray flux and the limitation of the detector array length (only 50 mm) this configuration imposed a relatively compact measuring geometry with modest magnification factors. Nevertheless, the facility proved to be adequate for the measurement of most of the low-density samples like: ceramics, aluminium and magnesium alloys, optical fibres and various isolator materials. However, for higher density metallic samples the relatively low energy, low power X ray source led to major difficulties in achieving good quality reconstruction images, especially due to beam hardening artefacts.

3.1.1 Low density materials

Among most important low-density materials relevant for fusion application are ceramics tritium breeders. Figure 3 shows the images reconstructed for two high voltages for a relatively large channelled ceramic sample at a low magnification. One can say that this is a satisfactory result showing accurately the structure integrity. Since the pre-filtering was insufficient (thicker pre-filters would reduce too much the flux) the higher voltage measurement displays higher beam hardening effects (apparently lower density in the inner part of the image).

![Reconstruction images of ceramic structure. The size of the hole is 1.5 mm and the wall is 0.25 mm thick. Magnification = 1.2.](image)

Figure 3: Reconstruction images of ceramic structure. The size of the hole is 1.5 mm and the wall is 0.25 mm thick. Magnification = 1.2.

A finer structure from a similar material was imagined in Figure 4 at higher magnification. Again, one can say that the facility performs very well for this type of material.
Figure 4: Reconstruction image of ceramic structure (U=50 kV; I=140 μA). The size of the hole is 1.0 mm and the wall is 0.15 mm thick. The zoomed image on the right makes visible some voids in the structure walls even at modest magnification (6.5).

Figure 5: Reconstruction image of a sinterized magnesium alloy tensile probe (U=90 kV; I=90 μA, Magnification 5.5). Sample has a trapezoidal cross section with dimensions 4x7mm².

Figure 5 introduces a reconstructed image of a tensile sample of high-density sinterized magnesium-titanium alloy. The space and density resolution of the instrument proves to be
sufficient to reveal the crack defects in the core of the sample (see the zoomed image on the right).

3.1.2 **High density materials**
Most relevant high-density metallic materials are composed of steel and similar alloys. In our test measurements we considered typical SUS316 steel probes.

Figure 6 presents a reconstructed cross section of a typical miniaturized tensile sample made of SUS 316. Despite significant beam hardening and some geometrical artefacts one remarks the ability of the instrument to visualise the two voids defects on the right half of the sample.

![Figure 6: Reconstruction image of a SUS 316 tensile sample (U=90 kV; I=90 μA, Magnification 5.4). Sample dimensions are 6x1 mm². Beam hardening effects are especially strong along the longer side.](image)

Zoomed image on the right shows the two voids in the right half of the sample cross-section.

Figures 7 and 9 represent cross sections of reconstructed distribution for complex structures containing SUS 316.

In figure 7 we show an aluminium cylinder with 12 drillings of 0.5 mm diameter, 9 holes are filled with SUS 316 pipes with interior diameters of 50, 100 and 200 microns. In order to simplify the description one segmented the image according to the grey level histogram of figure 8. On the left one shows the high density SUS pipes. Despite the geometrical distortions one can see most relevant details of the structure. On the right one shows the inferior part of the grey levels histogram. This corresponds to aluminium structure but also includes the steel pipes and especially their beam hardening artefacts. We should notice that the artefacts caused by beam hardening have a severe non-linear behaviour in complex structures. Considering this result one should conclude that for structures containing significant amount of high density metals the performances of a low energy microtomographic facility are rather poor.
Figure 7: Reconstruction image of an aluminum-steel structure (U=90 kV; I=90 μA, Magnification 6.5). Steel insertions have exterior diameter of 0.5 mm and interior diameter of 50, 100 and 200 microns. Picture of the right shows very clear the beam hardening artefacts due to highly attenuating steel insertions.

Figure 8: Gray levels histogram of the reconstruction image of figure 6. The histogram is useful for the segmentation procedure.

Next example is a reconstruction of a structure composed only of SUS 316. Figure 9 represent the reconstructed cross section of a SUS bundle of 7 pipes of 1 mm interior diameter enclosed in an outer pipe of 5 mm exterior diameter. All pipes walls are 0.25 mm thick. Again, one remark that beam hardening effects are very strong with the attenuation coefficient of the centre pipe more than 80% lower than the attenuation coefficient of the outer pipe. In the right picture one shows a zoomed image of the pipe welding.
3.2 Design considerations

The main consequences of these test measurements for the design phase were:

- In order to allow higher magnifications (higher space resolutions) one should use a longer linear array detector. Also the energy limitations (untill 100 keV) of the currently available linear arrays should be addressed. A common solution of these problems has been found in discussions with Hamamatsu Photonics Ltd.Co. specialists. This consists of a montage of two line sensors each of 50 mm length in a tandem and use of slanted optical fiber plates to avoid direct exposure of the photodiode sensors to X ray radiations, which is responsible for the high energy limitation.

- The main objectives of the subtask could not be achieved if we would not employ a microfocus X ray source able to deliver as high as possible energy. There are two main commercially available options: sealed and open type microfocus tubes. Taking into consideration the cost and operation requirements of different available options we have chosen to use a microfocus sealed tube of maximum high voltage, currently available on the market (150-160 kV).

These conclusions were confirmed by further test measurements on high-density metallic samples with the improved line detector (100 mm and working energy up to 150 keV) and a higher energy (150-160 kVp) microfocus X ray source and numerous interactions with specialists from the X-ray equipment manufacturers. As a result of these interactions our initial design has suffered some very positive changes. Most significantly, we realized that the X-ray detection systems has so impressively developed from the moment of the proposal of this project that we can now build a fully 3D cone-beam tomograph with no increase in the total project budget. Obviously, this expanded by far its capabilities with main additional features: real time radiography and high magnification inspection at oblique angle.
4. Microtomography system fabrication

Following the evaluation procedure a cone-beam X-ray microtomographic system has been constructed at the National Institute for Laser, Plasma and Radiation Physics (NILPRP), Bucharest-Magurele, Romania.

A general view of the microtomography system is presented in Fig. 10. The main components are: the open type microfocus X-ray source, the 2-D X-ray detection system and the micrometric sample manipulator. The X-ray source is mounted on a manually adjustable positioning support. The X-ray detection system is supported by a manually adjustable positioning device eventually mounted on a micrometric translation axis. The whole tomographic system lies on an optical table which is placed inside a lead shielding cabinet. Two Dual CPU (2x2Ghz) networked workstations are used for the data acquisition and control and for the 3-D tomographic reconstructions and visualizations.

As pointed out in the previous paragraphs the selection of optimum tomographic configuration and components is based on test measurements of miniaturized sample mock-ups carried out on existent tomographs as well as on fully 3-D Monte Carlo simulations of X-ray radiation generation and transport. The designed targets for space resolution, magnification and reduction of beam hardening are optimally satisfied by a combination of the image intensifier detection system and the open type 160 kVp X-ray source. This configuration allows us to reduce the beam hardening artifacts and in the same time to achieve very large magnification factors (up to 2000).
4.1 Description of system’s key components

4.1.1 X-ray source
The system is provided with an open type 160 kV microfocus X-ray source manufactured by PhoenixX-ray. Its main applications list includes typical inspection tasks in the automotive, aerospace, steel and electronics industries and industrial and medical computer tomography. At a feature recognition down to 1 µm, the minimum object-focus distance is 0.4 mm to provide highest geometrical magnifications at short focus-detector distances. Consequently this ensures a reasonable longitudinal dimension of the tomographic system: a distance of 1000 mm from the beryllium window to image intensifier input window would guaranty a magnification factor of about 2000. Another advantage consists in its replaceable filament. A manual adjustable table was constructed for fine tuning of the vertical and transversal positions of the X-ray source. The X-ray controller is provided with a key-activated control to ensure that X-rays will not be generated when the key is removed.

4.1.2 Detection system
The detection system is based on a SIRECON 17-2 HDR-M X-ray image intensifier, manufactured by Siemens Medical Solutions. It is a large diameter (169 mm useful entrance field and 20 mm output window) imaging tubes that convert low contrast images into visible light images. The image intensifier is coupled with a CCD-Compact-Camera. For images acquisition is used a 10 bits analog frame grabber IMAQ PCI-1409 from National Instruments. Due to a newly developed CsI input phosphor screen the X-ray image intensifiers provide high DQE (detection quantum efficiency) of 65% and high-quality images with good resolution and contrast (the modulation transfer function is less than 1% for 0.1 Lp/mm). The distortion of the lens has deliberately been selected to obtain compensation of the image intensifier distortion. The reduction in distortion for the total imaging chain (image intensifier + lenses + CCD) is in the range 3÷7% depending on the reproduction scale. The detector is placed on a manually adjustable table with vertical and transversal positioning. Alternatively the transversal position of the detector can be adjusted using a computer controlled micrometric motorized stage.

4.1.3 Micrometric manipulators
An essential component of a microtomograph system is the micrometric manipulator. Motorized stages are combined to assure a maximum degree of freedom in sample positioning for both tomography and high magnification radiography. The sample manipulator includes two translations and one rotation axes in order to realize an X-Z-θ assembly. The X stage has a relatively long travel distance (500 mm) for implementation of the magnification degree of freedom. Its positional repeatability is less than 10 microns. It is placed along the axis between the X-ray source and the detection system (X axis). The Z axis is used for sample elevation control and has a travel distance of 300 mm and positional repeatability better than 5 microns. The Z axis has a large enough loading capacity (6 kg) for supporting the rotary stage as well as the sample itself. The reinforced motorized rotary stage has a positional accuracy 0.03° or less and positional repeatability 0.01° or less
The motorized stages are computer controlled simultaneously by a single control unit via a serial RS232 (or USB) port by a Mark-204 (Sigma-Koki, Japan) stage controller. Trigger output signals makes it possible to synchronize the stage movements with external measuring devices as image acquisition. Additionally, a joy pad (control pad) is provided for manual operation, memory settings, and programming.
4.1.4 Optical table

The optical table which holds the microtomography assembly and the manual manipulator (detector and source positioning supports) were designed and constructed in our institute. The dimensions of the optical table are 1890 x 800 mm with a height of 300 mm from the ground level and the possibility of a vertical adjustment of ± 30 mm. It is provided with a rectangular screw holes matrix which allows the precise mounting of the microtomograph components.

4.1.5 X-ray shielding cabinet

The X-ray cabinet was designed and manufactured in our laboratory in accordance with the international ionising radiation safety regulations and is rated for continuous operation in normal working environments. In the calculations the weekly dose limit of 0.02 mSv is used, as derived from the dose limit for the general public (1 mSv/year). The X-ray shielding cabinet is made of steel and lined with lead of maximum 6 mm thickness on the front side of the cabinet and minimum 4 mm for the side facing the room wall and the ceiling. The lead shielding is covered by aluminium plates. A special attention was paid to solve the problem of the overlapping of the lead sheaths at joints, corners, penetrations, floor and door. Figure 11 sketchily illustrates the technical solutions we have implemented.

Figure 11: Typical design of fastening methods and openings in primary barrier: longitudinal section (left) and transversal section (right).

The door of the cabinet X-ray system has a two safety interlocks. For collision avoidance the inside of the cabinet is continuously watched by a video camera and it is provided with fans for extracting the exceeding heat.
4.2 Image acquisition and 3-D reconstruction

The image acquisition, 3-D reconstruction and reconstructed volume visualization are carried out on two networked Dual CPU (2 GHz, 2GB) workstations. The reconstruction software is implemented such that the reconstruction time roughly matched the acquisition time so at the end of the measurement a 3-D volume rendered image is available.

Image acquisition and motorized stage control programs are developed on the base of the National Instruments LabView Virtual Instruments library. Despite progress in exact cone-beam reconstruction, approximate cone-beam reconstruction remains the 3-D CT working horse, especially in the cases of incomplete scanning and partial detection. Furthermore, approximate reconstruction is usually associated with higher computational efficiency, and may produce less image noise and ringing. Feldkamp-type cone-beam reconstruction is the main stream of approximate cone-beam reconstruction [1]. The Feldkamp (FDK) cone-beam algorithm is an ingenious adaptation of the weighted filtered backprojection algorithm for equispatial rays.

The Feldkamp filtered backprojection formula

The unknown distribution function at position \((t,s,z)\) is given by:

\[
f(t,s,z) = \frac{1}{2} \int_0^{2\pi} \frac{D_{SO}^2}{(D_{SO} - s)^2} \int_{-\infty}^{\infty} p_{\beta}(Y,Z) h \left( \frac{D_{SO} t}{D_{SO} - s} - Y \right) \frac{D_{SO}}{\sqrt{D_{SO}^2 + Y^2 + Z^2}} d\beta dY
\]

where: \(t = x \cos \beta + y \sin \beta\), \(s = -x \sin \beta + y \cos \beta\), \((Y,Z)\) are the detector pixel coordinates in a plane translated such that the q-axis is superimposed on the z-axis (Fig. 1).

![Feldkamp algorithm cone-beam geometry](image)

Figure 12: Feldkamp algorithm cone-beam geometry

Explanation of figure:

- Oxyz - reconstruction coordinate system; sample rotates around z-axis
- Dpq - planar detector coordinate system
SO  - source-object distance  
SD  - source-detector distance  
β  - angle of rotation of sample (equivalent picture – angle of synchronous rotation of 
source-detector assembly )

The cone beam reconstruction algorithm can be broken into the following three steps:

**Step 1: weighting projections**
Multiply projection data, \( P_\beta(Y,Z) \), by the function \( Dso/(Dso^2 + Y^2 + Z^2) \) to find the 
weighted projections.

**Step 2: filtering projections**
Convolute the weighted projection with the ramp filter \( h \) by multiplying their Fourier 
transforms with respect to \( Y \). Note this convolution is done independently for each elevation 
\( Z \).

**Step 3: backprojection**
Finally, each filtered weighted projection is backprojected over the three-dimensional 
reconstruction grid. The two arguments of the weighted projection represent the 
transformation of a point in the object volume into the coordinate system of the tilted fan. 
The FDK algorithm is highly parallelizable and hardware supported. The FDK is an 
approximate method because only those points of the object that are illuminated from all 
directions can be properly reconstructed. In a cone-beam system this region is a sphere of 
radius \( D_{so} \sin(\Gamma_m) \) where \( \Gamma_m \) is half the horizontal cone angle. Outside this region a point will 
not be included in some of the projections and thus will not be correctly reconstructed. The 
main limitation occurs at relatively large cone angles.

### 4.3 Microtomography system: Overall Performances

Finally, the overall specifications of the system are synthetically presented in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Specifications</th>
</tr>
</thead>
</table>
| 1 Microfocus X-ray source | Max. high voltage: 160 kVp  
|                  | Max power: 20 W  
|                  | Feature recognition: 1 µm  
|                  | Min object-focus distance: 0.4 mm  
|                  | X-Ray cone: 170°                  |
| 2 Detector elements | 512x512  
|                  | 1024x1024 (maximum)               |
| 3 Micrometric manipulator | travel 500 mm, loading capacity 30 kg  
|                  | travel 300 mm, loading capacity 6 kg  
<p>|                  | accuracy 0.03°, loading capacity 20 kg                  |
| 4 Magnification Factor | &lt;2000                              |
| 5 Source-Detector Distance | 1000 mm typical                  |
| 6 Source-Object Distance | &gt; 0.5 mm typical                  |
| 7 Spatial Resolution | ( \pm 10 \mu m )                  |</p>
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Density Resolution</td>
<td>&gt;0.5%</td>
</tr>
<tr>
<td>8</td>
<td>Digital Output&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>10 bits</td>
</tr>
<tr>
<td>9</td>
<td>Scanning Time&lt;sup&gt;4)&lt;/sup&gt;</td>
<td>&lt; 10min. (720 angle)</td>
</tr>
</tbody>
</table>
| 10 | 3D Reconstruction Time<sup>3)</sup>              | < 2min. (256x256, 256lines)  
|    |                                                | <5min. (512x512, 256lines)  
|    |                                                | <20min. (1024x1024, 512 lines) |
| 11 | Effective Area of Detector                      | 169x169 mm²            |
| 12 | Probe Dimensions                                | Diameter <40 mm        
|    |                                                | Height <500 mm         |
| 13 | Projection Number                               | 360                    
|    |                                                | 720                    |
| 14 | Scan Method                                     | Cone beam CT (<512lines)  
|    |                                                | Full scan (360deg.)    
|    |                                                | Short Scan (180deg.+1/2 fan angle) |
| 15 | Output data format                              | Uncompressed 16 bits integer |
| 16 | Geometry Calibration Program                    | Center of Rotation     
|    |                                                | Vertical & Horizontal Alignment |

<sup>1)</sup> Minimum distance from X-ray focus to the object is 0.4 mm.  
<sup>2)</sup> Mainly limited by stage control accuracy.  
<sup>3)</sup> Digital output from frame grabber NI – PCI-1409.  
<sup>4)</sup> Assuming 0.5sec/angle and stage motion.  
<sup>5)</sup> Based on Dual Athlon, 2000MHz PC.

### 5. Testing the microtomography system

The first testing step was an extensive campaign for tuning the system parameters, as geometrical system alignment and linearization of the detector response. Next step one focused on achieving high-magnification and high-resolution radiography images of miniaturized samples in order to assess the performance of the system as a NDT inspection tool. Finally, the ability of the system to obtain high quality 3D representations of the investigated miniaturized samples was tested on a large variety of high-density metallic and low density materials with complex structures.

#### 5.1 Micro-radiography

Micro-radiography images of a set of representative samples proved that the space resolution and the penetration power are sufficient for most of samples relevant for fusion material studies. Figure 13 shows examples of high resolution micro-radiography inspection.
Figure 13: High resolution micro-radiography: inkjet printer head, vertical dimension of ink nozzle array is 5 mm (top-left) and detailed nozzle view, approx. 50 μ diameter (top-right); detail view of a chipset with 20 μ thick bonding wires (bottom-left), thermal effect of electron beam overexposed plastic scintillator, minimum visible bubble size 10-20 μ (bottom-right).

The micro-radio/tomography analysis is probably the only method able to assess the structural integrity of activated and completely assembled rigs, test modules and Li-target backwall. Currently, we are cooperating with the designer and manufacturer of these components in order to initiate an experimental campaign of micro-radiography analysis. Following figure illustrates the ability of our system in finding hidden defects of complex metallic structures (Figure 14).

In addition to fast NDT inspection of micro-structures and mechanical integrity, real-time radiography is a very powerful tool for the visualization of evolving processes as fluid flow or in-situ analysis of fusion material samples under mechanical and/or thermal test.
5.2 Microtomography

Finally, the newly developed tomography system has been successfully validated by tomographic measurements. 3-D reconstructed images demonstrate that the designed parameters of the image quality have been achieved. Our computer system consists of two networked Dual CPU (2 GHz, 2GB) workstations. Data acquisition, motorized stages control and images pre-processing are implemented using LabView library functions. The 3-D tomographic reconstructions are obtained by a highly optimized computer code based on a modified Feldkamp algorithm. Our reconstruction program is coded in a mixed language (Fortran90/C++) for speed-up optimization and friendly data management. For the postprocessing of the 3-D reconstructed arrays we use a leader of the industry software product (VGStudioMax) from Volume Graphics GmbH, Heidelberg, Germany. Figure 15 shows an application of the multiple features of this software.
For the testing phase of the newly developed microtomography system we considered main types of samples relevant for fusion material community: high-density metallic and low density materials as ceramic. In the first category most representative are steel samples. Figure 16 includes examples of microtomography of SUS miniaturized samples and of a multimaterial composite. As SUS probes we investigated a traction sample and a silphon tube. The multimaterial composite was produced for geometry and density calibration of the system. It includes metallic materials as diverse as silver, copper and kanthal plus an organic insulator. From the inspection of the reconstruction one can conclude that the microtomography system allows us to achieve best performances, well above the initially designed parameters.
Figure 16: Examples of microtomography of miniaturized samples - from left to right radiography, density plot and sagittal view: SUS traction probe 2 mm diameter (top); geometry and density calibration sample made of copper tube 2.2 mm, silver central wire 0.5 mm and coiled kanthal wires 0.18 and 0.08 mm (middle); steel silphon of 6.5 mm diameter (bottom).
Figure 17: Examples of microtomography; density plot representation: complex structure as geometry and composition of a vacuum tube (left), fragment of a soldering droplet 3 mm characteristics size (middle) and fractured drill of 2 mm diameter (right).

Figure 17 introduces some 3-D reconstructions of real life samples as: complex structured vacuum tube, soldering material ball and a fractured drill. Our system proved to be able to carry out high quality tomographic images.

Figure 18: Micrometric voids, inclusions and cracks in the ceramic core of a carbon film resistor.

For low density materials we have tested the system on a miniaturized ceramic sample. As can be seen on figure 18 all typical defects – voids, inclusions and micro-cracks – can be revealed. In this particular experiment, where the overall magnification was about 50 we assess the defect detectability limit around 10 microns. As we have the ability to work with maximum magnifications over 1000 one can estimate that the defect detectability limit can be lowered to few microns.

5.3 Reduction of the beam hardening effects
Beam hardening effects are the main challenge for the application of the microtomography technique to the NDT analysis of the miniaturized fusion material samples. Beam hardening artifact consists of an elevated density displayed on the perimeter of a uniform density probe
and a corresponding density depression in the probe’s core region. We focused our efforts to design and test various methods, both experimental and computational, to the reduction of the beam hardening effects.

Two ways were followed:

- Optimization of X-ray source parameters and filters design for narrowing the X-ray energy spectrum;
- Pre-processing of the projection data for the correction of the X-ray transmission non-linearity.

In both methods we use extensively fully 3D Monte Carlo simulation of electron and X-ray generation and transport.

By adequate selection of the X-ray source, high voltage, and of the pre-filter materials and thickness one could significantly reduce the beam hardening effects and consequently the need of employing highly sophisticated segmentation methods.

**Monte Carlo simulation**

Obviously, the optimisation of the tomographic measurement by experimental selection of a large set of parameters is a very laborious procedure and the result is not always guaranteed. Therefore, development of a numerical simulation procedure is highly desirable. One goal of this subtask was to build a working environment for a realistic numerical simulation of a tomographic measurement. To this purpose we used the integrated TIGER series (ITS) time-independent multimaterial and multidimensional-coupled electron/photon Monte Carlo transport code.

Figure 19 shows a sketch of a slice-by-slice tomography configuration used in our fully 3D Monte Carlo simulations. This configuration allows us to study the effect of any important element as: target material, pre and post-filters, X-ray energy spectra etc.

![Figure 19: Set-up of a three-dimensional Monte Carlo simulation](image)

- **e** electron beam
- **T** tungsten target
- **F0** intrinsic beryllium filter
- **F1** lead filter
- **F2** copper filter
- **P** cylindrical probe
- **F3** aluminium post-filter
- **D** linear detector array
- **S** transmitted X-ray profile

Photon flux profile along the linear detector array, the most important quantity in a tomographic measurement can be realistically simulated. The optimisation procedure requires
to pre-filter the X-ray beam for narrowing the energy spectra, at the same time monitoring the spectra evolution into the probe structure for maximum absorption contrast.

High performance microtomography on fusion material samples of advanced steel alloys would require, in addition to beam parameters optimisation, the application of active methods of beam hardening reduction. Linearisation of the non-linear dependence of the line integral on the ray path through different steel thickness is a very useful method.

Spectrum of incident X-ray beam on the sample from a transmission tungsten target irradiated with a 100 keV electron beam was filtered by 0.6 mm Cu plate.

Measured points are obtained by a Monte Carlo simulation of the transport of the above X-ray spectrum in steel probes of different thickness. Energy deposition into a 0.4 mm thick CsI scintillator is accurately described. Linear curve is obtained by multiplication of the spectrum-averaged attenuation coefficient of steel with the thickness of the probe.

Figure 20: Simulation of the non-linear dependence of the line integral on the ray path (radiological path) through different steel thickness.

In Figure 20, one describes the main steps of this technique, the determination of the non-linear dependence followed by the pre-processing of the projection data by multiplication with pre-calculated correction factors. Obviously, determination of the non-linearity of the line integrals by accurate Monte Carlo simulation instead of laborious experiments is always desirable.

Figure 21 (left column) shows quite significant residual beam hardening artifact even after filtering the X-ray spectrum with 0.6 mm copper foil. By applying the linearization correction of the transmission curve procedure one obtains a substantial reduction of the density depression in the probe’s core region (right column). Further refinement of the beam hardening reduction method is under progress.
5.4 Geometrical measurements by micro-tomography

Classical Reverse Engineering techniques use optical scanning or more classical measuring devices. In these cases, only the outside of an object is captured. Layer-wise milling and scanning are able to scan the inside. Advantages of CT scanning over optical scanning or conventional measuring methods are multiple. The major advantage is the ability to measure internal geometries. Compared to optical scanning, coating with reflective material can be avoided, steep slopes and undercuts are not a problem to scan and the setup is easy. Compared to layer-wise milling and scanning, it is important to realize that CT scanning is non-destructive and has a fixed working cost. The necessity to embed an object in epoxy for layer-wise milling and scanning can result in a high variable cost. Compared to conventional measuring, the advantages are mainly the ease and speed and the large collection of data points.

An interface between scanner images and CAD, Rapid Prototyping (RP) or Finite Element analysis is necessary. It should provide 2D and 3D advanced visualization, segmentation and measurement tools.

Several segmentation techniques are provided for processing different kinds of images or structures.

- By defining one threshold, the segmentation volume is defined by all pixels with a grey value higher than this threshold. This is a very efficient technique for segmenting metallic structures within technical CT image data.
- It is also possible to define the segmentation volume by two thresholds. In this case, the segmentation volume is defined by all pixels with a grey value in between both

Figure 21: Reconstructed axial cross sections and diametral profiles of a uniform steel sample of 2 mm: without beam hardening correction (left), with linearization correction of the transmission curve (right). In both cases the X-ray spectrum was filtered by a 0.6 mm copper plate.
threshold values. This technique can be used for segmentation of lower attenuation components in composite materials or for segmentation of several structures in technical CT images.

- In order to define a more accurate threshold, especially important for technical CT scans, the profile function can be used. Along a user-defined line in the image a profile of the pixel intensities is displayed which helps at choosing the correct threshold. Also the histogram function can help by defining the different upper and lower threshold when an object of different materials has been scanned. Manual editing is an efficient tool to remove inherent image artefacts.
- It is also possible to create different segmentation objects and visualized them separately or together (as well in the 2D module as in the 3D module), each marked by a specific colour.

Following is an example of the image processing techniques required for the segmentation and features measurement on a 3D reconstructed distribution.

![Fig. 22: Density plot of a fragment of a fully 3D tomography reconstruction (left) and cross section of the 3D distribution (right), segmented by value.](image)

Fig. 22: Density plot of a fragment of a fully 3D tomography reconstruction (left) and cross section of the 3D distribution (right), segmented by value.

![Fig. 23: Automatic identification of components in cross-section represented in Fig. 1b. Segmentation is performed by thresholding.](image)

Fig. 23: Automatic identification of components in cross-section represented in Fig. 1b. Segmentation is performed by thresholding.

This example illustrates components identification and labeling using 4-connected objects [2]. The perimeter of the objects in resulted binary image was determined. Example of automatic computation of a set of measurements for each labeled region is given in Table 3.
6. 3-D image reconstructions data base of the miniaturized samples

In addition to the fabrication of the microtomography system a consistent database for storing tomographic images of the miniaturized samples in different development and testing phases has been also designed and implemented. Taking into account the heterogeneity of the platforms used for data acquisition software (LabView) and for reconstruction software (mixing Fortran 90 and C++) we decided to use Microsoft Access for the database development. A VBA application was also developed in order to ensure user-friendly information retrieving of the parameters of the tomographic process: geometry and setup of the experiment, projections, reconstructed images, reconstruction parameters, storing type of information. The database is implemented to allow convenient data exchange, processing and interpretation of 3-D NDT data within the IFMIF fusion materials community.

![Image of database structure](image)

**Figure 24:** The structure of the database.

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7. Outlook and conclusions

Consistent with the task objectives a cone-beam X-ray microtomographic system has been designed, fabricated and tested at the National Institute for Laser, Plasma and Radiation Physics (NILPRP), Bucharest-Magurele, Romania. The system consists of an open type microfocus X-ray source, a 3D micrometric translation and rotation samples manipulator and a 2-D X-ray detection system based on large area image intensifier and fast-scan CCD. The selection of optimum tomographic configuration and components is based on test measurements of miniaturized sample mock-ups carried out on existent tomographs as well as on fully 3-D Monte Carlo simulations of X-ray generation and transport. The 3-D tomographic reconstructions are obtained by our highly optimized computer code based on a modified Feldkamp algorithm.

The new developed tomography system will allows us to provide the fusion materials community with a unique instrument for NDT inspection of individual miniaturized samples as well as for verification of irradiation capsules integrity. The micro-radiography analysis is guaranteed for feature recognition down to 1 micron. Currently, in tomography measurements with moderate magnification (approx 50) we assess as defect detectability a limit around 10 microns. As we have the ability to work with maximum magnifications over 1000 one can estimate that the defect detectability limit can be lowered to few microns. In addition, we proved that beam hardening artifacts are reduced by a correction method based on X-ray spectrum filtering and the linearization of the transmission curve. Also, we introduced a segmentation procedure for accurate geometrical measurements by micro-tomography.

A consistent data base of the 3-D image reconstructions of the miniaturized samples in different development and testing phases was designed and implemented.

In the process of using this facility for extensive NDT inspection of fusion materials miniaturized samples the main goal is to establish the reference design for transmission micro-tomography system for IFMIF environment conditions. An effort will also be made for development of new methods to cope with the challenging problem of beam hardening in high density materials. Fully 3D Monte Carlo radiation transport simulations combined with validation experiments represent our main tools in approaching these problems. In addition new inspection configurations will be investigated in order to visualise irradiation capsules integrity.

During the irradiation campaigns in IFMIF, one produces highly radioactive miniaturized samples and capsules. During the year 2003 activity is launched for the elaboration of a technical concept of an emission tomography system for the examination of the structural integrity of activated and completely assembled rigs, test modules and Li-target back-wall of the IFMIF.

References