CCMX FORM 5 - INTERIM SCIENTIFIC REPORT
Analytical Platform Project

This report should be sent by e-mail in both Word and pdf fomats to reporting@ccmx.ch

Scientific reporting questions may be addressed to: nathalie.jongen@epfl.ch

Platform	[X] NMMC
Project title	**Gantry-based X-ray Phase Contrast Scanner for MicroCT Applications**
Principal investigator (PI)	**Prof. Dr. Marco Stampanoni** **ETH Zürich and Paul Scherrer Institut**
Co-applicant(s)	Christian Kottler, Senior R&D Engineer, CSEM Zürich,
Industrial partner(s)	Bruno Koller, CEO SCANCO Medical AG
Reporting period	**01.01.2012 to 31.12.2012**

I, Prof. Dr. Marco Stampanoni, hereby declare that the information in this report is complete and true.

The report has been approved by all the project partners.

Signature	Date	Location
	11.1.2013	Zürich/Villigen

CCMX FORM 5 – INTERIM SCIENTIFIC SUMMARY
FOR THE PERIOD COVERING 01.01.2012 TO 31.12.2012

1. Executive Summary (max. 10 lines)

The project foresees the development of a high-energy, gantry-based phase contrast system based on grating interferometry. This approach allows recording absorption, differential phase and dark-field signals simultaneously, returning information about sample attenuation, electron density and small-angle scattering power. During the first year we formulated the conceptual design, involving multiple operation options at different energies and with/without gantry rotation. We built-up an experiment to test the feasibility of high-energy phase contrast based on a novel, "edge-on" grating illumination scheme and, in parallel, we designed a preliminary version of a "gantry-ready" system.

2. Project goals.

The goal of the project is to develop a table-top, gantry-based X-ray phase contrast microCT scanner. It will be dedicated to a broad field of applications, such as biomedical imaging, inspection and non-destructive testing. Its specific strength resides in high sensitivity for weakly absorbing materials with a resolution down to a few micrometers. At the end of the project, the system will be available in the framework of the CCMX analytical platform.

The two main goals are:

(i) Development of a gantry system (accommodating the X-ray source, image detector and interferometer), to enable the measurement of realistic samples, in the best case in-vivo samples, including dedicated acquisition protocols to allow efficient and fast measurements.

(ii) Access to high-energy applications with demanding geometries (compact setups and fan beam illuminations), requiring the design of innovative grating solutions.

3. Summary of milestones and achievements during the reporting period (max ½ page).

The project essentially poses two main challenges. These are, on the one hand, the development and realization of a new grating-based imaging concept to access high X-ray energy and, on the other hand, the implementation of a compact grating interferometer on a gantry system for fast and high resolution data acquisition. The first challenge will be addressed by introducing a novel illumination scheme dubbed "edge-on grating illumination", the second will be realized with the use of conventional, planar gratings. The project has been designed in such a way that – at the end – both approaches could have been combined. Due to the significant cut to the budget, however, we expect this last step not to be realized within the context of the present project.

The requirements for high energy, large field of view and short (compact) source-to-detector distance demanded for a completely new way of grating design and fabrication. We introduced a novel grating interferometer scheme – called "edge-on grating interferometer" – that addressed all those requirements. The new design allows for arbitrary aspect ratios and geometries. Both are key features needed to allow high-energy operation (to cope with the high penetration depth of high-energy photons) and compact geometries (to cope with very divergent beams). A feasibility experiment has been designed and implemented (see detailed description in Section 4. We expect first results in February 2013.

The implementation of the interferometer on the gantry system foresees two different grating configurations. Because an "ideal" grating configuration is always a trade-off between different parameters, these two configurations provide embodiments that are optimized for complementary properties, such as, for example, compactness, sensitivity, or flux. The fabrication and procurement of these gratings has been settled: some of them are commercially available (flat gratings), are manufactured according to our design by a company ("edge-on" gratings) or are issued within the framework of a proposal we successfully submitted to the Karlsruhe Nano Micro Facility (KNMF).

At the time of writing, the conceptual design of the system has been accomplished and we are entering the design phase.

4. Description of the achieved results (max. 4 pages).

We describe here the progresses on the conceptual design, the hardware specification and procurement as well as the specification and manufacturing of the gratings.

Up to now, the aspect ratio (pitch/(2*height)) has been the limiting factor for grating interferometry at high X-ray energies: current fabrication methods are limiting this number to about 50. For the specified energy range (up to 120 keV), aspect ratios of at least 400-600 are necessary. With our novel grating interferometer approach, based on the edge illumination of the gratings, arbitrary aspect ratios can be achieved, opening the path to the high-energy range. Although this advantage comes at the expense of a limited field of view in the vertical direction (parallel to the tomography axis), large field of view imaging is still possible -- without increasing the dose -- by translating the sample. The field of view in the horizontal direction, which is the most important one for tomography, can be very wide, since the technique allows curved grating shapes. Therefore, besides enabling access to high aspect ratios, the edge illumination method is also compatible with diverging beam geometries. For a divergent beam, the gratings require a curved shape, which is of fundamental importance when designing compact, X-ray tube based systems. Gratings without such a curvature would not match the travelling direction of the wave front at positions far from the optical axis and would thus reduce the usable field of view. The radius of curvature of such gratings must be specified already at the level of the (LIGA) mask design. This means that such radius is fixed and that, consequently, that specific grating can only be used for one source-to-grating distance at a given energy.

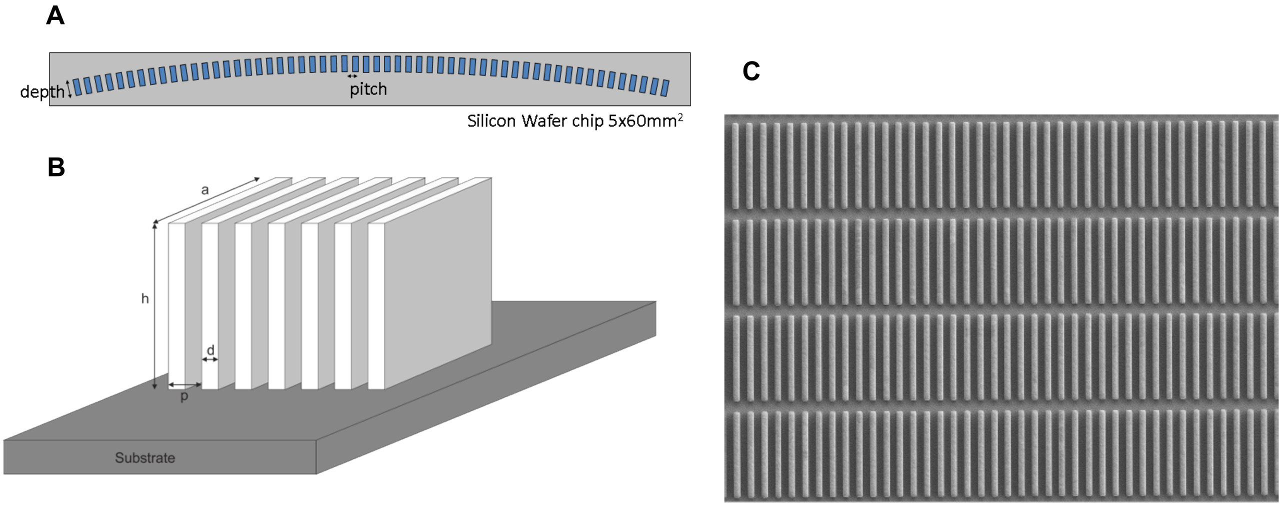

Fig. 1: **A**: Sketch of the top-view of a grating with a curved shape to be used for edge on illumination. **B**: Sketch of the front view of such a grating, with lamellae on top of the Silicon substrate. **C**: SEM image of the X-ray lithography mask for one of the gratings designed for this project. The interruption of the vertical grating lines is necessary to guarantee stability.

The design of such gratings is far more challenging than the standard approach (front illumination) and clearly played a central role in this project. The German company Microworks GmbH has been selected for manufacturing those gratings, since they have access to LIGA, the key X-ray lithography technique for our purposes. In a first step, an X-ray absorption mask was produced: several grating parameters including pitch, duty cycle, depth (grating length in beam direction), height (defining the vertical field of view) and radius of curvature have been calculated and “snapped” onto the mask design. On a single wafer, 16 gratings were fabricated for seven different interferometer geometries and for three different energies. As mentioned, we are pioneering a novel approach for gratings design and, as a consequence, many fabrication parameters had to be optimized first. Due to the complexity of the process, this was a very time consuming task. At the time of writing, we obtained a first gratings set but its quality is not satisfying. SEM investigations of the grating structures showed that the gratings contain large fractions of defective structures or areas where the metal (gold) has overgrown during electroplating. High-resolution X-ray images of the gratings acquired in-house by using synchrotron radiation microscopy confirm these findings. A next set of gratings, manufactured with further optimized parameters, is now in production and we expect it in Feburary 2013.

Currently, an optical table, an X-ray source, a detector and the interferometer itself are now set up and ready for the first experiments. Due to the highly demanding precision of the grating alignment, a lot of effort has been put into the development of the mechanic related to the interferometer. Goniometers and multiple linear stages allow the gratings to be oriented and translated in all the necessary direction. A sample stage with a rotation axis is available for tomographic imaging.

For the X-ray detection a MYTHEN (single photon counting) detector, developed at Paul Scherrer Institut, has been interfaced into the system and will be used for the experiments. The pixel size is 50 microns and the sensor is 8mm thick (silicon strip), directly converting the photons into an electric signal. Although the quantum efficiency may drop severely at the aimed high X-ray energies, the low count rate signal is, due to the single photon counting feature, at least noise free.

For the interferometer to work properly, an appropriate filtering of the X-ray spectrum has to be developed. From theoretical analyses we know that the grating interferometer generally allows spectral bandwidths of approx. 10% around the design energy. Especially at higher design energies, the low energy photons from the tungsten Bremsstrahlung have to be filtered out. Minimizing the spectral bandwidth and maximizing the flux lead to an optimization problem. We decided to optimize the flux for a given design energy and bandwidth as a function of the thickness of different filter materials.

In addition to the filtering, the MYTHEN detector allows accessing some spectrally resolved data, which implies that the low energy (but also high energy) photons, which are outside of the acceptable window, can be easily removed from the recorded image.

The SCANCO scanner VivaCT 40 has been taken as a reference for the development of the gantry-based grating interferometer setup. In particular, we considered the mean working energy (20-50keV), the sample diameter (≤4cm), the spatial resolution (≈10μm) and the set-up length (≤50cm). Grating parameters have been specified accordingly keeping an eye on the fundamental constraints dictated by the existing fabrication technology.

We specified the following two set-up options:

Option	Design energy (keV)	l (cm)	d (cm)	p_0 / H_0 (μm)	p_1 / H_1 (μm)	p_2 / H_2 (μm)
A	30	44.0	4.4	- / -	3.6 / 38.0	2.0 / 50.0
B	40	20.1	20.1	5.0 / 100.0	5.0 / 51.0	5.0 / 100.0

Both options offer some specific advantages but have also some limitations. Option A doesn't use a source grating and therefore, the full flux of the source can be used. However, this option requires very small grating periodicity p_2 resulting in a (fabrication-limited) maximal depth of H_2=50μm. On the other hand, in option B all gratings have the same periodicity, i.e., $p_{0,1,2}$=5 μm, which is comparably moderate. Thus, the absorption grating G2 can be produced with a depth of H_2=100 μm. These two analyser gratings will be produced by CSEM silicon-based technology. In order to correct for the beam divergence of the compact set-up, the wafers will be mounted on a bent holder. Our preliminary experimental tests already showed that such gratings, installed on a curved surface (R≥40cm), could successfully correct for the visibility loss due to a divergent beam impinging on a flat gratings. However, the source grating in option B cannot be realized on silicon because of the very small (few cm) radius of curvature required. This "bendable" grating will be manufactured within the framework of a proposal submitted to the Karlsruhe Nano Micro Facility (KNMF).

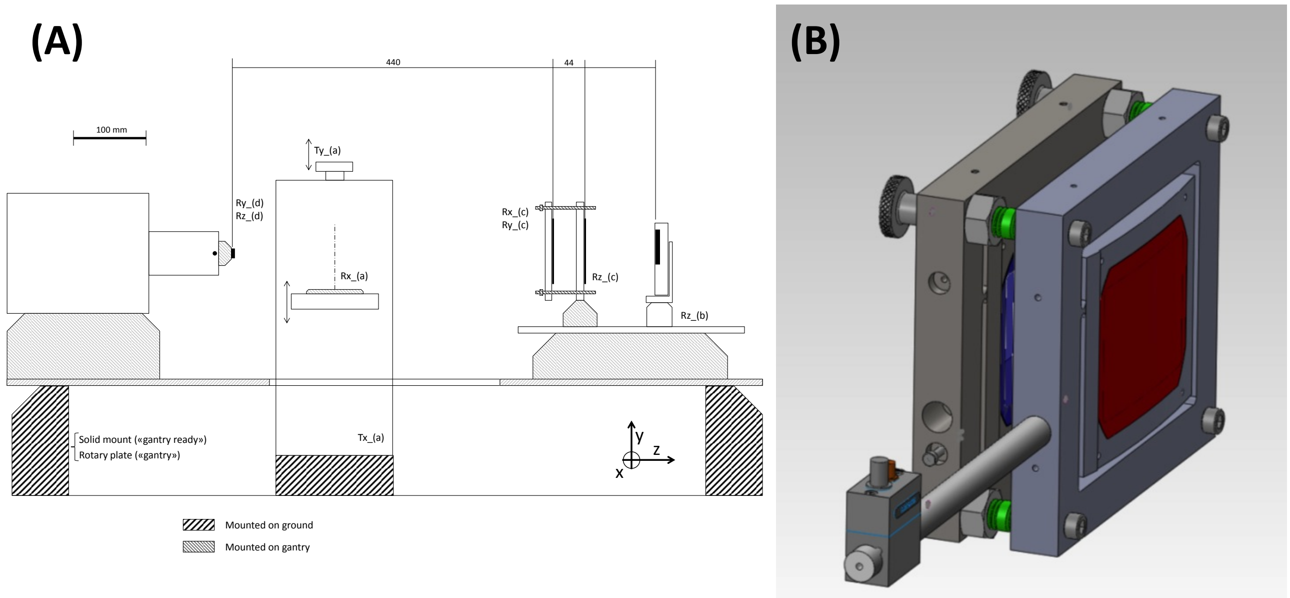

Fig. 2: (A) Sketch of “gantry-ready” grating interferometer. The X-ray source, the detector as well as the gratings with their holders are mounted on a bench, which can be fixed to the gantry (rotation) table. During the commissioning phase, the bench will be immobilized, while sample rotation and translation will be performed with additional stages. (B) 3D visualization of the holder assembly for the phase- and the analyser grating (G1 and G2). The actual gratings are mounted onto the cylindrically shaped surface of the holders in order to compensate for the beam divergence of the compact set-up. Tilts angles are adjusted with integrated piezo motors.

Fig. 2 A shows a sketch of the grating interferometer set-up. The conceptual design is such that the complete interferometer, including the image detector, the X-ray source and all grating holders are mounted on a bench. In the first phase, this bench is statically mounted on a table support while the sample positioning as well as the sample rotation for the tomographic measurements is realized by a translation- and a rotation stage based from “outside” of the bench. We dubbed this system’s embodiment “gantry ready” since it will be used for the characterization of the system, the test measurements as well as for the development of the acquisition protocols WITHOUT gantry-rotation. The final design foresees the bench to be mounted on the gantry system provided by SCANCO Medical AG.

During gantry rotation, the stability of the relative alignment of the components becomes a critical issue. Tolerances for the corresponding accuracy for all the degrees of freedom were specified. One of the most critical parameter is the rotation (around the optical axis) of the G2 with respect to G1. Therefore, we suggest one single frame that provides all degrees of alignment for G2 with respect to G1 (see 3D-CAD view Fig. 2 B). The frame where G2 is mounted is connected to an outer frame by means of a flexible bridge: a piezo manipulator, attached to that outer frame, pushes against the actual, inner frame and thereby aligns the gratings with a precision which we estimated to be sufficient for our needs.

Next steps foresee construction of that holder, design of the bench and several mechanical parts as well as the procurement of the components.

5. Assessment of project progress.

Did the project run as planned?

[ ] Yes [X] No

Were the project goals reached? [] Yes [X] No

If no to either question, please describe why.

The project had a very slow start-up due to the significant budget cut to one of the project partners. Because of this, we had to revise our plans and adapt the strategy to the reduced resources, which resulted in a delayed start.

The company in charge of manufacturing the edge-on gratings experienced unexpected, severe, difficulties in fabricating our structures, resulting in a 6 months delay in the delivery of the first bunch of gratings, which, as described in the report, was not satisfying.

As a consequence, we reached our milestone but not on time.

If PhD theses were being financed, did they progress as planned? [ ] Yes [ ] No

Thesis will be partially financed only from 2013 onwards, as well as for the PostDoc salary.

If no, please describe why.

Please indicate the anticipated date of the thesis defence of the PhD candidate(s). When available, please submit a copy of the thesis.

If the thesis has already been defended, please indicate the title and submit a copy of the thesis.

6. Have publications/presentations of the project results been made? [ ] Yes [X] No

If yes, please list the publications in the following order (please ensure to adhere to the formatting of bold, italics etc.):

First name initials Author 1, Last Name Author 1, First name initials Author 2, Last Name Author 2, etc, **Title**, *Journal*, volume (year), 1st page-last page.

Please organize the publications/presentations into the following categories:

1) reviewed ISI-publications,

2) non ISI-publications,

3) theses,

4) posters and talks at conferences

7. Have inventions been made and/or patents filed? [ ] Yes [X] No

If yes, please describe / if no, are any envisaged?

8. Description of industrial interest and involvement.

a) Describe the technical contribution to the project by the industrial partner(s)

SCANCO Medical AG granted us access to their gantry technology. This is a fundamental step and allows the project being carried out faster than originally planned.

b) Is a commercialization strategy in place?

Depending on the experimental results from our demonstrator, SCANCO Medical is considering DPC as a possible technology to be integrated in their systems.

9. Tell us about any success stories in your research projects: key scientific findings, interactions between research groups, prizes won such as best talk or poster… (10 lines max. per success story)

<u>Successful proposal submission at Karlsruhe Nano Micro Facility (KNMF)</u>

We successfully submitted a proposal for the fabrication source grating (on a bendable Ni substrate) to the Karlsruhe Nano Micro Facility (KNMF). Acceptance regulated by scientific excellence criteria. As a result, we will receive a set of 4 source gratings with an equivalent commercial value of about 20000 euros. The periodicity is 5 µm, depth about 100 µm with different duty cycle (0.2, 0.3, 0.4, 0.5). The Nickel substrate allows extreme bending and therefore these gratings can be used as source gratings, yielding an additional option to our conceptual design (better sensitivity but lower flux).

10. Please send electronically up to 5 pictures including a relevant caption (scientific topic or people) which may be used in CCMX publications (printed & website).

Our project has been selected for the CCMX 2012 yearly report. An article, including pictures, illustrating our activities will be prepared

11. Remarks.

Since we experienced very large delay in the startup of the project as well the delivery of the gratings, the (PSI) personnel costs will be charged to this CCMX project only from 2013 onwards.