1. Project Plan Factsheet

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Project Name	FleX-Ray
Project leader	Prof. dr. K.J. Batenburg (CWI)
Deputy project leader	Prof. dr. ir. E.N. Koffeman (NIKHEF)
Task leader	Dr. D. van Loo (XRE)
Deputy task leader	Dr. H.R. Poolman (ASI)

2. What is the goal of the project?

2.1 Scientific background

Tomographic scanning provides the unique ability to see inside the object, by combining X-ray imaging with rotation, acquiring projection images from a range of angles. These projections can even capture the 4D (= 3D space + time) dynamics of the object, provided that the rotation is sufficiently fast with respect to the timescale of the dynamical process. At the same time, X-rays can be harmful to the object under investigation, imposing a limitation on its use as a general investigative tool.
We are convinced that currently available X-ray tomography scanners use the X-ray dose in a strongly suboptimal way, radiating the full object rather than just the interesting areas and not registering the full physical information provided by each photon.

2.2 Research goal

The key research goal of the FleX-Ray project is to develop scanning techniques, detector technology and computational techniques that jointly provide a breakthrough in the information obtained from tomographic scans by maximizing the information obtained for a given dose level.

In particular, our objectives are to demonstrate strong improvements compared to the state-of-the-art in our ability to:

- Resolve and model object evolution during the scan, creating a 4D movie with similar dose compared to current 3D scans

- Segment and obtain structural characterization of the object, directly probing the material composition
- Locate and zoom into structures of interest in 3D, improving spatial resolution at a fixed dose level

To achieve this, we will establish the **FleX-Ray CT Scanning Lab**, which combines a unique CT scanner with highly flexible geometric capabilities, spectroscopic X-ray detection capabilities, and a powerful high-performance computing system.

From the initial design of the system and further on in its scientific use, we will combine the extensive expertise on tomography algorithm development of CWI with the expertise and experience of NIKHEF on X-ray detector development and experimental imaging. The design and operation of the FleX-Ray CT Scanning Lab will be carried out in close collaboration with our two industrial partners, X-Ray Engineering (XRE) and Amsterdam Scientific Instruments (ASI). XRE will lead the efforts to design the CT scanning system and ASI will contribute hardware and expertise to equip the scanner with spectroscopic capabilities.

The FleX-Ray CT Lab will be first-of-its-kind to combine

- Real-time 3D Tomography, linking a dedicated GPU-cluster with novel reconstruction algorithms directly to the scanner, providing direct insight in the object structure.
- Spectral Tomography, yielding detailed information on the wavelength-specific absorption behavior of the object, facilitating direct compositional analysis.
- Adaptive Scanning, locating the interesting regions in 3D during the scan and zooming into these regions.

The FleX-Ray CT Lab will provide both CWI and NIKHEF with a leading edge to develop groundbreaking research in the rapidly developing field of tomographic imaging.

2.3 Final delivery/goal of the project.

The FleX-Ray project will have a duration of five years. By the end of the project we plan to have realized the following goals and deliverables:

(1) Operational and highly utilized CT scanning lab based on the unique combination of a customized CT scanner with highly flexible geometric capabilities, spectroscopic X-ray detection capabilities, a direct link to a powerful high-performance computing system, and real-time reconstruction and control software. The lab will play a pivotal role in:
   a. Developing novel proof-of-concepts for combining advanced scanning and computation
   b. Developing hardware and algorithms for spectral CT

   c. Establishing and fostering collaborations with a broad range of experimental and computational imaging groups.
   d. Demonstrating state-of-the-art capabilities to commercial and academic partners.

(2) Realized demonstrators, documented in published journal articles, that push forward the state-of-the-art in:
   a. 3D and 4D adaptive scanning, where the geometrical parameters of the scan are adapted to the observations.
   b. 3D and 4D spectral scanning, where the information from different energy levels are combined to yield high-contrast element-specific images.

(3) Newly acquired research projects focused on various fundamental research questions, as well as industrial and biomedical applications, enabled by the CT scanning lab.

2.4 Project funding and investment.

The **FleX-Ray Lab** project is carried out as a collaborative effort involving four parties: CWI, NIKHEF, XRE, and ASI.

1. **CWI** will contribute:
   a. Cash budget for acquisition of the non-spectral components of the CT-scanning system.
   b. In-kind manpower for developing the FleX-Ray CT lab, corresponding software development, and performing research using the new facility.
   c. Cash and in-kind support for preparing and sustaining the actual working space for the FleX-Ray CT lab.
2. **NIKHEF** will contribute:
   a. Cash budget for acquisition of the spectral components (X-ray source and motor control) of the CT-scanning system.
   b. In-kind manpower for developing the FleX-Ray CT lab, management and reponsibility of radiation regulations, technical operation, and performing research using the new facility.
3. **XRE** will contribute:
   a. In-kind manpower for design and construction of the CT scanning system.
   b. In-kind manpower for servicing of the CT scanning system.
   c. In-kind manpower for performing research using the new facility.
4. **ASI** will contribute:
   a. In-kind budget for installing an array of Medipix spectroscopic detectors, including processing hardware and software.
   b. In-kind manpower for servicing of the Medipix detectors.
   c. In-kind manpower for performing research using the new facility.

TODO: the contributions and obligations of all partners must be described in more detail and converted into EURO amounts (cash and in-kind).

Proposal from Joost:
- CWI purchases the non-spectral scanner from XRE. CWI also provides in-kind contribution of both service (computational technician) and research staff.
- XRE provides in-kind contributions by discounting w.r.t. their regular price model and providing support and collaborative development work
- NIKHEF purchases a secondary X-ray source specifically optimized for spectral tomography (and possibly additional motor units for control, if needed). NIKHEF also provides in-kind contribution of both service (radiation expert, lab technician) and research staff.
- ASI provides Medipix detectors and in-kind contributions for service work and collaborative development work.

When/if it comes to matching of investments, this will be carried out separately between CWI/XRE and NIKHEF/ASI respectively. Therefore, the budget contributions for the non-spectral and spectral parts of the project can be separated.

3. Workplan

The FleX-Ray CT Lab project will consist of seven workpackages. The workpackages 1-3 deal with the design and implementation of the scanning lab infrastructure, consisting of the CT-scanner and computational components. The workpackages 4-7 focus on different research topics that will be developed and investigated once the scanning lab is operational.

WP1. Non-spectral Scanner design and construction *(Implementation)*
Implementation leader: XRE Scientific leader: CWI **Description** In this workpackage a highly flexible CT scanning system will be designed and constructed that is suitable for fast scanning and offers a high degree of geometric flexibility. **Functional requirements** • Scans objects at varying resolutions, up to approximately 20 cm in size • Combines the goals of high flux and fast rotation • Offers full automated flexibility in positioning of the object, source, and detector • Offers a high-speed non-spectral detector system with high data-transfer rates

- Can be fully controlled directly from our own software
- Can be connected by a high-speed network interface to a GPU computing cluster, already available at CWI.

XRE will be responsible for creating the formally specified design, based on discussions with CWI and NIKHEF. XRE will coordinate the design of the system with the activities of WP2 (design of spectral scanner), resulting in a joint scanner design for the two types of scanning. XRE will be responsible for the construction of the system.

Schedule:

30/06/2016: coarse design consensus, decision on scanner dimensions so that granite base plate can be ordered

30/09/2016: detailed design consensus, start of full ordering and construction process

31/03/2017: scanner at CWI

WP2. Non-spectral Scanner design and construction *(Implementation)*

Implementation leader: XRE
Scientific leader: NIKHEF

Description
In this workpackage the CT scanning system of WP1 will be augmented with spectral imaging capabilities based on the Medipix detector.

Functional requirements
- Integrates a separate array of Medipix spectral X-ray detectors that allow to discriminate the photons by wavelength
- Allows to perform experiments where spectral and non-spectral imaging techniques are compared in identical geometrical setups.
- Can include an additional secondary X-ray source (using a different energy compared to the primary source, to allow for fully simultaneous dual-energy acquisition

XRE will be responsible for creating the formally specified design, based on discussions with NIKHEF, CWI, and ASI. XRE will coordinate the design of the system with the activities of WP1 (design of non-spectral scanner), resulting in a joint scanner design for the two types of scanning. ASI will be responsible for providing the Medipix detectors and control logic, both hardware and software. XRE will be responsible for the construction of the system.

Schedule:

30/09/2016: detailed design consensus, start of full ordering and construction process

31/03/2017: scanner at CWI

WP3. ASTRA Toolbox Integration *(Implementation)*

Scientific leader: CWI

Description

In this workpackage a direct two-way link will be developed between the CT scanner + control software, and the ASTRA toolbox running on a compute cluster at CWI.

Functional requirements

- Geometrical setup of the scanner can be retrieved and converted to an ASTRA toolbox scanning geometry. Vice versa, an ASTRA toolbox scanning geometry can be converted into a sequence of control instructions for the scanner.
- Detector data from the scanner can be retrieved and converted to an ASTRA toolbox data object for further processing and reconstruction at full framerate.
- Acquisition

CWI will be responsible for developing the software interface between the native control software of the CT scanning system and the ASTRA toolbox. The work will be carried out in close collaboration with XRE, where XRE will provide technical details of the control software and carry out adaptations of the software when needed.

Schedule:

01/01/2017: start of software development

30/09/2017: software platform operational

WP4. Flexible geometry reconstruction *(Research and Implementation)*

Scientific leader: CWI

Description

In this workpackage, algorithms and software will be developed to perform scanner control and reconstruction for emulating a range of commonly used CT scanning geometries.

Geometries

- Circular cone-beam (standard geometry)
- Helical cone-beam (standard geometry)
- Conveyer belt (Stationary cone-beam with transversally moving object)
- Tomosynthesis
- Laminography

- Region-of-interest reconstruction

CWI will be responsible for the work in this workpackage.

Schedule:

01/10/2017: start of work

31/03/2018: completion of software development and experiments

WP5. Fast adaptive scanning *(Research)*

Scientific leader: CWI

Description

In this workpackage, algorithms and software will be developed to perform fast adaptive scans of both static and dynamically changing objects, detecting interesting regions in the sample in real-time and zooming into these regions adaptively.

Workflow for the scanning process:

- Continuously create fast scan of full object
- Compute 3D reconstruction in real-time
- Automatically detect formation of defects
- Zoom into ROI where defects are forming
- Continue scanning at high resolution

Research questions

- How to develop new reconstruction algorithms that are both (real-time) fast and capable of accurate reconstruction from limited data.
- How to adapt the scanning process to maximize future information gain
- How to incorporate prior models of the underlying physical dynamic processes to increase spatial and temporal resolution

Scanned Objects

- Static 3D printed objects with various types and sizes of image features
- Dynamic fluid flow test setup (fluid through pores)
- Dynamic granular flow test setup (beads in motion)
- Dynamic mechanical motion test setup (clockwork)
- Biomedical objects (flower, insects)

CWI will be responsible for algorithmic research underlying this workpackage. XRE and NIKHEF will actively contribute in the preparation of suitable test objects. NIKHEF will be involved in fine-tuning the experiments and interpreting the results.

Schedule

01/01/2018: start of work

01/01/2020: demonstrators available for all five cases

01/06/2020: results published in several high impact articles

WP6. Spectral CT scanning *(Research)*

Scientific leader: NIKHEF

Description

In this workpackage, experimental and computational techniques will be developed for spectral tomography.

Research questions

- How to choose source and detector parameters in an optimal way for different types of samples
- How to reconstruct element-specific images from Medipix detector data with high spatial resolution and chemical sensitivity

Scanned Objects

- Biomedical objects (flower, insects)
- TO BE COMPLETED

NIKHEF will be leading the activities in this workpackage, in close collaboration with CWI (reconstruction) and ASI (Medipix).

Schedule

01/01/2018: start of work

01/01/2020: demonstrators available for different types of objects

01/06/2020: results published in several high impact articles

WP7. Real-Time Adaptive Spectral CT: making the most out of each photon *(Research)*

Scientific leader: CWI, NIKHEF

Description

In this workpackage, the experimental and computational techniques developed in the workpackages WP1-WP6 will be combined into the realization of a completely new scanning technique, combining spectral CT with real-time reconstruction and adaptive acquisition.

Research questions

- How to extend the techniques for real-time tomography to spectral CT
- How to tune the experimental parameters (source settings, detector settings, geometrical settings) to the available information during the scan.

Scanned Object

- TO BE COMPLETED

CWI and NIKHEF will jointly lead this workpackage, which must be carried out in close collaboration.

Schedule

01/01/2019: start of work

01/01/2021: demonstrators available for different types of objects

01/06/2021: results published in several high impact articles

4. Infrastructure

4.1 General Labspace

The Flex-Ray CT Scanning lab will be established at the ground floor of CWI, where a large room is available. As the CWI building has not been designed for laboratory work, it will be necessary to check whether structural adaptations must be made to walls, and a system for secure entrance must be installed. CWI will consult with the NIKHEF radiation expert for these matters.

4.2 Sample preparation

CWI does not have sample preparation options. Test objects will be used from a variety of sources, prepared by NIKHEF, XRE, and ASI. CWI plans to create a series of specific test objects using 3D printing.

4.3 Computing infrastructure

The Computational Imaging group of CWI has a powerful compute cluster installed in the server space on the third floor of the CWI building. In the scanner design process, it will be important to realize a full-speed connection between the scanner data output and control and this (Linux-based) compute facility.

4.4 Data Storage

The Computational Imaging group at CWI currently does not have access to large-scale dedicated storage for storing CT datasets. Options for data storage will be considered as part of the laboratory setup.

5. Project Safety

The X-ray tube(s) of the FleX-Ray CT system will be limited to run at voltages of less than 100kV.

The FleX-Ray CT system will be fully contained in a lead-shielded casing, allowing the system to be used when people are present in the lab space, without the need for additional shielding.

The FleX-Ray CT system will only be taken into commission after risk analysis and authorization by the NIKHEF radiation expert, Ing M. B.H.J. (Marcel) Vervoort. When the lab is in use, it will be subjected to the "Regulations for Use Radioactive Sources/Material and X-ray Devices" of NIKHEF. Access to the FleX-Ray CT system will be limited to staff that has followed the appropriate training, in accordance with the regulations.

6. Useful documentation

Radiation guidelines of NIKHEF:
https://wiki.nikhef.nl/detector/pub/Main/Safety/130528_Rules_Usage_radioactive_sources__X-ray_devices_version_1.pdf