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Summary

Immediately after its discovery in 1895, X-ray radiation started to make an enormous contribution to society. Fields like medical diagnostics, materials inspection and protein crystallography rely heavily on the imaging and analytical capabilities of X-rays. Notwithstanding major developments over the past century, there are three important intrinsic limitations to X-ray tubes, the conventional X-ray sources...
used in the lab: their relative low intensity, the poor coherence of radiation and the selective availability of X-ray energies. Since the late 1970s synchrotron sources have become available, which offer high-brilliance, coherent and energy-tunable X-rays, but these are only available at a limited number of specialized facilities worldwide, providing scarce beam time – at a high cost – outside the scientists’ lab. There is no synchrotron source in The Netherlands.

Here, we propose to develop and apply a revolutionary, compact, affordable and miniaturized alternative to a synchrotron facility – a tabletop Inverse Compton Scattering (ICS) source. The physical basis is the ICS process in which photons from a laser beam are bounced off a relativistic electron beam, turning them into X-ray photons through the relativistic Doppler effect. Already described theoretically decades ago, the enabling technology necessary to materialize such a source, has only very recently matured into robust components. Ultra-low-emittance electron guns, compact X-band accelerator technology and high-power pulsed lasers have become available only recently. This now brings the ICS source for in-situ applications of high-energy X-rays within our reach. In combination with the newest X-ray detectors (Medipix) the tabletop ICS source will constitute an extremely sensitive, on-site, non-destructive tool for imaging and analysis. We plan to use the ICS source where it will be most effective: in a clinical environment for medical imaging, inside the materials scientist’s laboratory for work on new materials and in the museum conservation studio for the study of important artwork. Our plan includes key partners, covering both the instrumental development and the relevant user communities, as well as academic and industrial stakeholders.

**Key words**
X-ray analysis, materials science, medical radiology, cultural heritage

II. **VOORSTEL INHOUDELIJKE UITWERKING**

A. **SCIENCE AND TECHNICAL CASE**

**INTRODUCTION**
Since their discovery by Wilhelm Röntgen in 1895, X-rays have become an indispensable tool for scientists. The strong interaction between X-rays and electrons results in a lower transmission in materials that consist of atoms with a higher electron density. In this way, X-rays give a view of the inside of the human body (see Fig. 2), composite materials, historical art objects and archaeological objects. By applying different angles and computer reconstruction, a 3D tomographic image can be rendered. The first Computed-Tomography (CT) scan of the human body was made in 1969, and this technique is now routinely applied in hospitals worldwide on a daily basis.
Figure 2: An early X-ray image taken by Wilhelm Röntgen of the hand of his wife.

Since 1912, diffraction has enabled the detailed study of atomic nanostructures with monochromatic X-rays. The unraveling of the structure of DNA (1952) with X-ray diffraction (XRD) is a well-known example (see Fig. 3). An important energy-dependent technique is X-ray fluorescence (XRF), which allows for elemental analysis of, for example, materials and paint layers.

Figure 3: On the right the X-ray diffraction image (nickname “photo 51”) from which the well-known double helix structure of DNA (left) was retrieved.

Over the past decades, the use of large-scale synchrotron radiation (SR) facilities has made a big impact in various fields of science. Present-day synchrotron sources are multiple orders of magnitude more brilliant than state-of-the-art rotating anode X-ray tube sources. The tunable energy and high coherence of SR sources have set new standards in terms of spatial and analytical resolution and have resulted in the development of a range of new techniques. Recent improvements in detection and data-storage techniques nowadays allow for the study of dynamical processes down to timescales of seconds. The high brilliance also implies that a great number of samples can be characterized rapidly, even when only very small quantities of the material are available, such as in the life sciences. When very high X-ray energies are applied, deeper lying structures can be studied in transmission mode.

The Dutch community is fortunate to have the high-quality DUBBLE beamlines available at the European Synchrotron Radiation Facility (ESRF) in Grenoble for the characterization of nanostructures with SAXS/WAXS and EXAFS. The growing number of publications that are based on experiments on these beamlines are testimony of the important role synchrotron radiation currently plays in materials and life sciences.
High-intensity X-ray beams are of growing significance and in 2025, more scientists than now will rely on specialized SR facilities with good accessibility. However, the current synchrotron infrastructure is inadequate to accommodate the growing group of potential users, which increasingly restricts high-quality research. The Smart*Light (S*L) project we propose will provide a wider availability of high-intensity X-ray sources and thus reduce or eliminate the current physical distance between a synchrotron and a specialized experimental setup, museum, hospital, or industrial production facility. The Science Case paragraph below elaborates on how these high-accessibility S*L facilities will result in new breakthrough research. In this proposal the focus is on themes from materials science, cultural heritage studies and the medical sciences in which neither lab-sources nor synchrotrons provide a realistic alternative.

Better availability of high-intensity X-ray sources will enable a better understanding of our own body and the world around us. In this way, scientists can continue to strive to prolong life, improve the quality of life, and to make the materials our high-tech society demands.

The Smart*Light proposal relies on the same accelerator technology as the FEL-NL proposal of prof. Hoekstra. Both proposals aim at the development of revolutionary accelerator-based X-ray sources, but are highly complementary in their goals: while FEL-NL aims at a single large-scale facility enabling ultrafast science at soft X-ray wavelengths, the goal of S*L is a compact and tunable hard X-ray source. The FEL-NL and S*L projects will team up, together covering the X-ray needs of the Dutch scientific community and generating the critical mass required for further development of accelerator-based X-ray technology.

TECHNICAL CASE

Smart*Light X-ray facility: filling a gap

At present scientists in need of X-ray analysis basically only have two options: either use compact X-ray tube laboratory sources or apply for beam time at one of the 70-odd large synchrotron facilities available worldwide today. At present the highest performance in the lab is provided by micro-focus rotating anode X-ray tubes and the recently developed liquid-gallium tubes [Skarzynski 2013, Otendal 2008]. In X-ray tubes fairly large amounts of X-ray photons are generated, which are emitted in all directions over a wide range of X-ray energies, with the highest intensity peaking at the K-edge X-ray energy characteristic of the anode material. Synchrotron radiation (SR) X-ray sources came into existence in the 1950s as a byproduct of particle colliders for high-energy physics. Since the 1970s synchrotrons are specially designed for X-ray production, providing intense, highly directional and monochromatic X-ray beams, tunable from soft to hard X-ray energies. The choice between a compact and affordable X-ray tube source, which is always available, and applying for precious beam time at a synchrotron facility, with waiting times of months, is dictated by the X-ray energy and beam quality required for the application. Beam quality is usually expressed in terms of brilliance, which is the beam intensity per unit solid angle and per unit bandwidth. In Fig. 4 X-ray brilliance is plotted as a function of X-ray energy. The current brilliance for a typical bending-magnet-type beamline such as the Dutch-Belgian Beamline [DUBBLE] at the ESRF synchrotron in Grenoble is many orders of magnitude higher than the high-brilliance non-synchrotron Excillum liquid-gallium and rotating-anode tungsten X-ray tubes. At synchrotrons, even higher brilliances can be achieved with insertion devices. Clearly, there is an enormous gap in performance between X-ray tubes and SR sources. As a result, many X-ray scientists who require other X-ray energies and/or better X-ray coherence than provided by X-ray tubes but do not really need the extreme SR X-ray intensities are still forced to apply for synchrotron beam time, simply for a lack of alternative. The high cost of synchrotron construction and operation however imposes severe limitations on available beam time. For scarce specialized beamlines, such as those providing hard X-rays with energies of 100 keV and higher, it is unavoidable that up to 90% of the proposals is rejected. Moreover, most experiments need to be confined to several days only.

With modern technology based on Inverse Compton Scattering (ICS) it is possible to realize a compact and affordable alternative to synchrotron light sources that is sufficiently coherent, narrowband and
tunable. Fig. 4 shows the brilliance that can be achieved with the Smart*Light (S*L) ICS source we propose, in comparison with the above-mentioned currently available X-ray sources. The Smart*Light (S*L) ICS source offers a brilliance orders of magnitude higher than the best X-ray tubes over a wide range of energies. Note that the S*L ICS source will actually surpass bending magnet SR sources in brilliance at hard X-ray energies – essential for many applications in materials science. In addition, as will be elaborated below, it will provide a unique divergent-beam mode of operation not possible in synchrotrons, which is highly desirable for phase contrast imaging (PCI). PCI requires a high degree of X-ray coherence but not necessarily a monochromatic X-ray beam. PCI is essential for visualizing structures in biological soft tissues and therefore extremely relevant for medical applications. It is also of great interest for studying structures in high-density materials with small density differences and therefore small absorption contrast.

In the facility we propose both the X-ray beam divergence and the X-ray energy can be changed very rapidly while conserving beam coherence. The X-ray brilliance and operational flexibility offered by Smart*Light combined with its availability and accessibility will not only make it into a serious alternative to SR sources but will also generate entirely new possibilities for X-ray analysis.

![Graph showing X-ray brilliance as a function of X-ray energy](image)

**Figure 4:** X-ray brilliance as a function of X-ray energy for synchrotron bending magnet radiation (SR BM) such as available at the DUBBLE beamline at ESRF, the proposed Inverse Compton Scattering (ICS) Smart*Light source, the liquid-gallium X-ray tube developed by Excillum and a rotating anode tungsten X-ray tube.

**Inverse Compton Scattering source**
Clearly ICS-based X-ray sources have great potential and could cater for current urgent needs. What are the reasons they have not appeared on stage until now? And what is special about the Smart*Light approach in particular?

In the Compton scattering process light is scattered from free electrons (see Fig. 5). If the electrons are moving sufficiently fast, the wavelength of the light scattered in the direction of the moving electrons, is decreased due to the Doppler effect. For electrons moving at relativistic speeds, i.e. close to the speed of light, the relativistic Doppler effect will convert incoming light at visible wavelengths into hard X-ray photons. If the electron beam and the laser beam are colliding head-on, the generated X-ray wavelength
\( \lambda_x \) is given by:

\[
\lambda_x = \frac{\lambda_0}{4\gamma^2}
\]

with \( \lambda_0 \) the laser wavelength, \( \gamma = 1 + U/(511 \text{ keV}) \) the Lorentz factor and \( U \) the electron beam energy. As an example, by colliding 400 nm laser pulses head-on with a 30 MeV electron beam, X-rays are generated with a wavelength of 0.28 Å, corresponding to an X-ray energy of 44 keV.

Figure 5: Inverse Compton scattering process

Unfortunately the probability for Compton scattering is extremely small. To generate a non-negligible X-ray photon flux one therefore needs to collide a high-power laser beam with an intense relativistic electron beam. The extreme laser and electron beam requirements are the main reasons ICS based X-ray sources have become a practical possibility only recently. Laser technology has developed tremendously over the last decade and a pulsed laser with the required high power is commercially available nowadays. Accelerator technology, however, is another story. In the first place, the coherence of the ICS X-ray beam depends critically on the electron beam quality, i.e. the electron beam brightness, which generally deteriorates during acceleration. The X-ray beam quality is therefore ultimately limited by the pulsed electron gun, which is not commercially available. In the second place, to generate hard X-rays the electrons have to be accelerated to several tens of MeV, which also requires specially designed devices. This can be done with either circulating accelerators or linear accelerators (LINACs). While circulating accelerators recycle the electron beam, enabling higher X-ray photon fluxes, this inevitably goes at the expense of electron beam emittance. Emittance is a beam quality parameter that determines how tight the beam can be focused. A smaller emittance implies a tighter electron beam focus, which directly translates into higher X-ray photon flux and better X-ray coherence. In LINACs the electron beam emittance can be conserved to a certain extent, but each electron pulse can be used only once.

In several recent developments [Lyncean, Bruni 2010] a hybrid approach has been chosen in which electrons are first accelerated with a LINAC and subsequently injected into a small storage ring to recirculate the electron beam. Although relatively compact, this still requires a LINAC and a ring several meters in size and a lot of concrete for shielding of the radiation that is produced when the electron beam is dumped. There are several additional drawbacks to this approach. First, recirculation of the electron beam spoils electron beam emittance and thus X-ray photon flux and coherence. Second, it is not possible to change the X-ray wavelength very rapidly since this requires changing the electron beam energy. If the electron beam energy is changed in a storage ring, alignment is lost, requiring readjustment of all bending and focusing magnets in the ring. Changing the X-ray energy in the Lyncean system [Lyncean], for example, takes several hours.

**Smart*Light approach**

**Accelerator:** In the Smart*Light proposal we opt for a compact, entirely LINAC-based approach. Using LINACs allows fast changing of the electron beam energy without losing alignment and thus fast tuning of the X-ray energy. Furthermore, in LINACs the low emittance of the electron gun can be conserved, enabling a smaller X-ray source size and thus a higher X-ray coherence. Finally, a LINAC-based system allows deceleration of the electron beam after the interaction region, which will minimize radiation
Electron gun: The coherence of the X-ray beam depends critically on the electron gun, which generally is not commercially available. The group of applicant Luiten at TU/e is specialized in low-emittance, high-brightness electron gun physics and technology. The group has a strong reputation worldwide with innovative gun concepts and record-low beam emittance [Engelen 2012]. A suitable 5 MeV RF photogun, in which electron pulses are generated by pulsed-laser photoemission, is available in the Eindhoven lab [Root 2009].

Pulsed laser: The required high-power pulsed laser technology is commercially available. The Coherent Legend Elite Cryo system, for example, produces >20 mJ, 30 fs, 800 nm pulses at 1 kHz repetition rate. By frequency doubling these can be readily converted into >10 mJ, 400 nm pulses, which will be used in the proposed setup. An essential ingredient of an ICS source is recycling of the laser pulses for which solutions have recently become commercially available [Dupraz 2014]. Optics and laser expertise is provided by the group of co-applicant Boller of U Twente. The Luiten group has extensive experience in RF-laser synchronization, which is necessary to make sure that the RF-accelerated electron pulses and the laser pulses arrive simultaneously at the interaction point [Brussaard 2014].

X-ray optics and detection: The ICS X-ray beams, with micron source sizes and milliradian divergences, are very similar to synchrotron beams. The curved mirror X-ray optics developed for synchrotrons [Dabin 2002] will therefore be suitable for envisaged Smart*Light applications such as Micro-Computed-Tomography (micro-CT). To make every X-ray photon count, we will make use of Medipix state-of-the-art X-ray detection technology, also developed by CERN in collaboration with Nikhef [Medipix]. The high detection efficiency of Medipix detectors is particularly important at high X-ray energies and for investigating soft materials susceptible to radiation damage. Medipix offers record spatial and temporal resolution; kHz read-out of large area detectors is presently under development. The Medipix detector is capable of extracting spectral information from a polychromatic X-ray beam, which is particularly useful in the divergent-beam mode offered by Smart*Light, which is discussed below (mode C in Fig. 7).

Medipix detectors are commercially available through the Dutch companies ASI and PANalytical, both part of Smart*Light consortium. General X-ray optics and detection expertise will be provided by PANalytical.

Summarizing, the Smart*Light approach combines state-of-the-art accelerator technology, laser technology and X-ray detector technology in a compact setup that will not only provide an alternative to SR in many applications but also generate entirely new possibilities for X-ray analysis. This is possible due to a unique collaboration between TU Delft, TU Eindhoven, U Twente, CERN and Dutch high-tech companies VDL-ETG, PANalytical and ASI.

Smart*Light setup and modes of operation

In Fig. 6 the Smart*Light setup is schematically illustrated (Figure 1 on the title page shows a more realistic 3D representation). Electrons (green) are produced by femtosecond laser photoemission and accelerated to 5 MeV in a high-brightness 3 GHz S-band RF photogun. A suitable RF photogun has been developed at TU/e and is available [Root 2009]. The electron pulses are subsequently accelerated in X-band LINAC sections. Each section boosts the electron energy by (maximally) 15 MeV. A set of solenoidal magnets controls the space-charge dominated electron pulses during acceleration. A quadrupole triplet magnetic lens focuses the electron beam to a tight micron-sized spot in the interaction region, where it collides nearly head-on with the laser beam (blue; angle between laser and electron beam exaggerated).
producing the hard X-ray beam (purple). In the setup shown in Fig. 6 the maximum electron energy is 35 MeV. Combined with 400 nm laser wavelength this results in a maximum X-ray energy of 60 keV. The maximum X-ray energy is adjustable by adding additional X-band sections. For instance, with three LINAC sections, the maximum X-ray energy (which scales with the electron energy squared) will be 120 keV. The electron energy, and thus the X-ray energy, can always be lowered easily and fast by simply changing the RF phase.

Figure 6: Schematic overview Smart*Light setup.

After the interaction region, the electron beam is diverted with a bending magnet (not shown in Fig. 6). Subsequently, the electron beam is either sent directly into a beam dump or first decelerated in a similar set of LINACs and then sent into a beam dump. In the latter case shielding requirements can be minimized. In Fig. 7 the optical cavity is schematically shown that will be used to recycle the laser pulses [Dupraz 2014]. To attain the ICS brilliance curve shown in Fig. 4, electron bunches with 10-100 pC charge have to be accelerated to several tens of MeV and focused to a 5 μm beam waist in the interaction region. The electrons are generated in microsecond bursts of 100 electron bunches, with the bursts coming at 1 kHz repetition rate. The 10 mJ, 400 nm laser pulses also come in bursts of 100 (recycled) pulses at 1 kHz repetition rate, resulting in $10^5$ electron-laser pulse collisions per second. The photoemission laser pulses that produce the electron bunches are generated with the same laser system so laser and electron pulses are perfectly synchronized.

In Fig. 7 the three modes of operation are schematically illustrated that are offered by the Smart*Light facility. Each mode is tailored to specific X-ray analytical methods:

A. < 5 μm spot size, ~1% bandwidth and ~1 mrad divergence (1 mm spot size at 1 m distance) for X-ray fluorescence (XRF) and X-ray diffraction (XRD);

B. < 5 μm spot size, ~1% bandwidth and ~1 mrad divergence focused using regular SR X-ray optics [Dupraz 2002] to (sub)micron spot sizes for micro-computed-tomography (micro-CT) and micro-XRD;

C. < 5 μm spot size, several 10 mrad divergence (spot size of a several cm at 1 m distance) for phase contrast imaging (PCI) (not monochromatic).
Figure 7: Three modes of operation of the Smart*Light facility.

In all modes of operation we aim for a root-mean-squared (rms) electron spot size in the interaction point (which is equivalent to the X-ray source size) of 5 μm at most. For X-ray energies of 10-100 keV this ensures coherence lengths of microns at a meter distance, ten times better than, for example, the Lyncean system [Lyncean]. To achieve 1% energy bandwidth the divergence of the electron beam should be ~1 mrad. The electron beam is identical in modes A and B. In mode C we aim for a divergent beam mode, which will allow illumination of large spots on the sample with a highly coherent beam and thus enable Phase Contrast Imaging (PCI). The divergent beam will inevitably result in a large X-ray bandwidth, which is however not a problem for PCI. Interestingly, mode of operation C is not possible in synchrotrons.

**Charged particle simulations**

To achieve the desired electron beam modes is far from trivial: highly charged electron bunches, which are necessary to achieve the desired X-ray photon fluxes, suffer from Coulomb repulsion, which leads to large spot sizes and general deterioration of the beam quality. To ascertain the feasibility of the Smart*Light approach detailed charged particle simulations have been done using GPT [GPT]. The particle tracking code GPT has been developed by the Dutch company Pulsar Physics and is used in more than 100 top accelerator labs worldwide. In GPT all accelerator components are modelled with realistic electric and magnetic fields. In addition the Coulomb repulsion between electrons in a bunch are taken into account.
Figure 8: Optimized settings obtained with GPT charged particle tracking simulations. Top: on-axis RF electric field strength $E_z$ as a function of longitudinal position $z$ at a certain moment in time required for accelerating electrons to 33 MeV. Bottom: on-axis longitudinal magnetic field strength $B_z$ generated by five solenoidal magnets, and magnetic field gradient $dB_z/dx$ (inset) as a function of longitudinal position $z$ inside the quadrupole triplet. The solenoidal magnets keep the highly charged bunches together during acceleration while the quadrupole triplet focuses the beam in the interaction point (red star). Blue curves: scenario A/B; red curves: scenario C.

The starting point of the simulations is the setup shown in Fig. 6. By varying the settings of accelerator components and the initial electron bunch conditions (16 degrees of freedom in total) the conditions in the interaction point have been optimized for mode A/B and for mode C. In Fig. 8 optimized settings are shown of the S-band RF photogun and the X-band LINACs (top panel) and of the focusing magnets (bottom panels). In both scenarios the electrons are accelerated to 33 MeV and collide with the laser pulses in the interaction point at 1.5 m from the gun. In Scenario A/B bunches with 9 pC charge are used, resulting in 3.5 $\mu$m rms spot size and 1 mrad rms divergence in the interaction point (see Fig. 9, left). In scenario C 33 pC bunches are used, resulting in electron beams in the interaction point which are not round due to the extreme focusing conditions: 1.5×3 $\mu$m rms spot size and 7×17 mrad rms divergence (see Fig. 9, right).

Figure 9: Electron beam spots in the interaction point for Scenario A/B and Scenario C.

From the results of the particle tracking simulations we conclude that Scenarios A, B and C can indeed be realized in the setup shown in Fig. 6. Actually we find that the performance is even better, in mode C much better, than expected. Note that the X-ray beam divergence in Scenario C is approximately twice the electron beam divergence, corresponding to 20-30 mrad rms divergence. These are settings optimized for
a specific - randomly chosen - energy, but similar results can be expected if an additional X-band section is added for higher X-ray energies. Finally, further optimization is possible since not all degrees of freedom in the design have been varied.

### SCIENCE CASE

**Medical radiology**

X-ray based medical imaging plays a key role in both biomedical research and clinical practice, e.g. through conventional X-ray imaging (e.g. fracture imaging and thorax imaging), fluoroscopy (for minimally invasive image-guided interventions) and 3D and 4D computed tomography (e.g. cardiovascular imaging). All these imaging technologies are based on differences in attenuation properties between tissues, resulting in contrasts primarily between bone, tissue and air. Phase contrast imaging (PCI) can potentially provide additional information, and there is great interest in the field of medical imaging to investigate its potential for many different applications. These application areas include, but are not limited to, the use of phase contrast X-ray in imaging of atherosclerosis and osteoporosis. Possible applications areas are many, and it is expected that the facility will be used by different research groups in medical imaging. For example, recently there has been significant progress in the application of PCI to mammography in a clinical setting [Castelli 2011, Auweter 2014]. Below the improved assessment of atherosclerosis and osteoporosis using PCI is discussed in some more detail.

1. **Phase contrast X-ray in cardiovascular disease**

   There is increasing evidence that the risk of cardiovascular events such as stroke and heart attack are primarily related to the microscopic composition of the atherosclerotic plaque in the vessel wall [Schaar 2004, Maseri 2003, Takaya 2006]. X-ray based cardiovascular imaging techniques, such as x-ray coronary angiography and coronary and carotid CT angiography, are established techniques for the assessment of vessel narrowing (stenosis), which is important for diagnosis and therapy planning (e.g. dottering and/or stenting). However, these techniques provide limited soft-tissue contrast and spatial resolution and are hence less suited for the visualization of the atherosclerotic plaque in the coronary and carotid vessel wall. A second limitation of conventional x-ray techniques is that coronary angiography requires arterial contrast agent injection, which is associated with a considerable risk. Finally, conventional x-ray techniques are not very well suited for the visualization of stents in relation to the vessel anatomy and the surrounding soft tissue, which limits their use for the design of optimal stents and therapy follow-up after stent placement.

![Figure 10: PCI at Pohang synchrotron facility in Korea [Kim 2007]. Left: In-vivo real-time synchrotron phase-contrast images of blood vessel (thoracic aorta) in live mice without contrast agents (arrow indicated). Right: 3D reconstructed image of atheromatous plaque in a blood vessel of a dead mouse obtained with PCI and B) Histological (microscopic) analysis of the matched lesion in the same mouse.](image)

Phase contrast x-ray imaging (PCI) has the potential to overcome these shortcomings. Owing to its...
intrinsic better resolution in soft tissue, phase contrast x-ray imaging enables vessel visualization without contrast agent. Recently, this was demonstrated at the Pohang synchrotron facility (South Korea) as depicted in Fig. 10 [Kim 2007]. Furthermore, PCI provides more detailed information on plaque composition (Fig. 10), which potentially provides valuable information on the likeliness of plaque rupture, and enables the study of plaque progression.

2. Phase contrast in osteoporosis

Osteoarthritis (OA) is the most common joint disease and one of the most frequent health problems in the elderly. In OA, both the trabecular bone (the porous bone below the growth plate) architecture and the cartilage quality and morphology change. Insight in the etiology of the disease is lacking and thus the development of new treatments is hindered. To study in depth the etiology of this disease, we need to monitor both bone and cartilage. At the moment, histology, micro-CT and MRI are used for this. Histology is a destructive technique, where large numbers of animals need to be sacrificed at different time points. With in vivo micro-CT, several longitudinal scans can be made in the same animal, but although the bone architecture can be imaged in great detail, the cartilage-imaging possibilities of this technique are limited. Using powerful MRI (3 Tesla) cartilage can be visualized with a resolution of approx. 0.3 mm in vivo. This is not enough to monitor accurately small changes in the initial phase of disease development; whereas in existing human OA the cartilage thickness can decrease by up to 0.4 mm per year, to monitor initial changes in the disease process resolutions below 0.1 mm will be necessary. PCI offers the unique possibility to image both soft and hard tissues at high resolution of 10 microns and in vivo (see Fig. 11).

Figure 11: With PCI / PCT trabecular architecture and cartilage morphology can be imaged simultaneously in vivo with a high resolution (Here, the condyle of the femur of a Pochard duck). This is not possible with other, currently used, imaging techniques. This will be extremely valuable in orthopaedic research in disease etiology and treatment modalities in e.g. osteoarthritis, the most common joint disease.

X-ray studies for the humanities

Already since the early 20th century, X-ray absorption radiography has been applied to provide insight into the making of an artwork, its conservation history, and current physical condition. Over the past decade, synchrotron facilities have set new standards in the analysis of artwork, shedding their light on degradation phenomena in pigments [Van der Snickt 2012], on the composition of Stradivari’s varnishes [Echard 2009] and on hidden paintings by Van Gogh and Rembrandt [Loeff 2012, Dik 2008]. However, the physical distance between the museum and a synchrotron facility poses a main obstacle for full exploitation of high-intensity X-rays. While radiography is routinely applied in many museums worldwide with lab-scale X-ray sources, transport of objects from and to large-scale facilities –if at all possible– usually is a logistical hurdle. This hurdle adds to the inconvenient ‘common’ waiting times between idea
and experiment. The Smart*Light project would give an immense boost to art and conservation research, as it would bring a high-brilliance beam to the objects of interest, rather than the other way around which is often risky, expensive, or impossible at all. It would thus facilitate detailed investigation of a multiple of the number of works that is currently eligible for examination. This includes top works that are usually under continuous display and that are only rarely allowed for transport outside the museum’s premises.

Smart*light’s beam geometries described in the technical paragraph (see Fig. 7) could be directly applied to many urgent questions relating to conservation issue and art historical problems. Beam geometry A would allow for the large-scale mapping of both elements (XRF) and crystalline phases (XRD) on artworks. The combination of elemental and crystalline distribution maps would provide us with coherent information on degradation mechanisms, without the need to take samples from artwork. Also, the scanning of large surfaces will give us representative information on the substructure of artwork. This ranges from overpainted masterpieces by Rembrandt or Van Gogh to early-medieval parchment, which was frequently re-used and thus contains multiple layers of ink. Figure 12 shows a good example of what Smart*light could achieve within such a cultural heritage setting.

Figure 12: The so-called Sophocles Manuscript, 10th century AD (Leiden University Library, BGP6011a). The surface ink covers traces of an earlier -as yet illegible- text of much older date. This enigmatic hidden text is of great philological interest, but has so far escaped all visualization efforts. A small part of the original text could be revealed by mapping the distribution of calcium (see inset) using tube-based XRF. Calcium proved to be present as trace element in the lower ink only. The total, tube-based acquisition time of this area (100μm spot size, field of view 3x3 cm) lasted 72 hours, preventing a full scan of the entire manuscript consisting of over a dozen pages. The much more efficient ICS source proposed in this project will bring visualization of the entire hidden text within reach.

Macro-XRF elemental scans have also been performed with great success on historical paintings. The artwork of virtually all great painters, including Van Gogh, Rembrandt and Picasso, usually contains hidden paint layers. This may relate to initial sketches by the artists themselves or later additions by restorers. Elemental distribution maps, can throw light on hidden layers as shown in figure 13 [Loef 2012]. However, surface shielding effects occur frequently due the presence of lead white in upper layers. In these cases, it would be desirable to use high-energy XRD mapping of crystalline phases with much higher penetration depth and higher analytical precision of individual phases, rather than elements. This cannot be done with low-intensity X-ray-tube-based setups and would be a breakthrough application for Smart*light in the study of paintings.
Figure 13: An example of how a combined XRF&XRD mapping approach could be used to scan entire surfaces of relevant paintings with Smart*light, rather than smaller windows.

Apart from visualizing hidden ink as shown in figure 13, Smart*light would be highly useful in visualizing the inner structure of all sorts of artwork. This could also include three-dimensional wooden objects, such as so-called prayer beads. Figure 14 shows the individual components carved from wood that were used in the fabrication method. In this case, PCI-based tomography was used to visualize the interfaces of individual components of the objects, shedding light on the production method of this highly intricate artwork [Reischig 2009]. This examination was carried out at beamline ID17 of the European Synchrotron Radiation Facility. Smart*light’s beam geometry C, however, would bring this capability directly to the museum and allow for much more systematic studies.

Figure 14: A small medieval ‘prayer bead’ from the collection of the Rijksmuseum, studied with phase-contrast based imaging at the ESRF, Grenoble. Aim was to visualize the fabrication method of this intricate piece of medieval microcarving. Smart*light would bring this capability directly to the museum.

**Materials science**

Materials are an essential part of our daily life. A growing demand exists for materials with specific requirements to enable new applications and to counter long-standing crucial challenges in materials performance. The field of materials science aims to improve existing materials and develop new ones by studying the relation between properties and structure. Scientists herein focus on the nanostructure, *i.e.* the structure on an atomic level, and microstructure, such as boundaries between structural elements,
crystalline domains and defects. The sub-nm wavelength of X-rays is highly suitable to resolve structures down to the atomic level in a non-destructive way, and the microstructure of materials has been studied ever since the discovery of X-rays.

The S*L project aims to have a high-brilliance source available as a standard facility at any materials science laboratory, providing a greater accessibility of high-intensity X-ray beams with high coherence and energy tunability. This will facilitate a new range of studies that require specific locational or temporal conditions. The main advantages to materials science research will be:

- Processes can be studied with characteristic timescales in the range of days to months (fatigue, ageing, corrosion) for which the conditions of traditional low-brilliance X-ray sources are unsuitable. Synchrotron beamtime is almost exclusively available to investigate processes with timescales of seconds to hours.
- No substantial waiting restrictions apply, which is especially advantageous for studying materials of which only small quantities can be produced. Rapid progress relies on short feedback loops. For synchrotrons, the time delay between idea and experiment is typically between 6 and 16 months.
- X-ray energies can be produced in the 100 keV range. These energies are required to study deeper lying layers in strongly absorbing high-density materials. There is very limited availability of SR beamlines that can provide this energy and none that facilitate studies that last more than several days.
- Specific sample environments can be accommodated, such as extreme pressures and temperatures. These require a specialized experimental setup that has to be built in place. In phase 4, dedicated facilities can be located at industrial sites such as for steel production or recycling.

Two fields in which a S*L device will be indispensable for cutting-edge materials science research are described below in detail, and an overview is given of other fields of interest. For none of these, suitable facilities are easily accessible.

1. Mitigating fatigue failure – Phase contrast imaging and diffraction with high energy (> 100 keV) X-rays

Fatigue occurs when a ductile material such as a metal alloy is subjected to repeated cycles of stress or strain. As a result, brittle fracture may suddenly occur even at stresses that are substantially lower than the yield stress of the material. The latter is generally determined by subjecting the material to a continuous load, for instance in a tensile test. In composite structures, fatigue can occur both in the structural elements and in the welds. Particularly troublesome is the abrupt and random nature of failure. Engineers attempt to design against fatigue failure by e.g. building in fallback systems such that not the entire system collapses, and by controlling the operational conditions. Extensive fatigue tests may further assist in assessing the maximum safe lifetime. In practice, however, economic considerations result in a substantial overstretching of the maximum design lifetime of bridges, power plants and railway switches. Moreover, fatigue depends on a broad variety of factors, including temperature, metallurgical microstructure, chemically reactive conditions and residual stress. To better predict maximum safe lifetimes and test new materials, investigations with high-intensity X-rays will be needed to acquire reliable experimental data [Herbig 2011, King 2011].
Figure 15: A 300 m long vessel carrying 7000 containers suffered a catastrophic hull failure in 2013, 300 km off the coast of Yemen.

The implications of failure can be severe. A multitude of disasters are directly related to fatigue failure in aircraft (e.g. El Al flight 1862 "Bijlerramp", 1992), trains (high-speed ICE 884, Eschede, 1998), oil platforms (Alexander L. Kielland, 1980) and ships (30% of all ship breakages (see Fig. 15), e.g. Liberty ships, World War II). Additional factors that may contribute to failure are embrittlement at decreased temperatures (enhanced ship breakage in cold waters, e.g. RMS Titanic, 1912) and upon exposure to hydrogen (Fukushima Daiichi Nuclear Power Plant, 2011), as well as extreme conditions such as high pressures (BP Gulf of Mexico Oil spill, 2010). Not at the ‘disaster’ level but at least highly annoying are train delays due to switch failures as the result of fatigue of welded components in rail tracks due to rolling contact. With the transition to ‘green’ wind energy, rolling contact failure in wind turbines also becomes of increased importance.

- Crack nucleation and growth. The mechanism of fatigue and the role of specific conditions are ill understood, especially in welds. Localized microscopic fatigue cracks typically nucleate at stress concentrators, such as the surface, along slip bands and grain interfaces (see Fig. 16) [King 2011].

Figure 16: Tomographic 3D rendering of a crack (white) with surrounding grains (coloured, semi-transparent). Colour denotes basal plane orientation. The location of the notch that was made to initiate the crack is indicated [King 2011].
Growth occurs progressively, with cracks eventually reaching a critical size, leading to sudden propagation and fracture of the structure. Extensive monitoring of crack nucleation and growth will give a deeper understanding of the causes of failure and timescales involved. This will in turn lead to improved design and operation. While a scanning electron microscope (SEM) can be used to monitor initial nucleation at the surface, obvious limitations are the inability to detect embedded cracks and even the depth and shape of surface cracks. Phase contrast imaging (PCI, mode C) with hard X-rays will enable full 3D imaging of sub-surface features. Cracks can be visualized due to their associated local lower density. PCI is also capable of scanning a large material volume without compromising the spatial resolution. This is especially relevant for high-cycle fatigue, which gives a very low crack nucleation density. The morphological changes that lead to fatigue failure are caused by structural processes with characteristic timescales in the order of minutes to months. Long-term availability of high-intensity X-rays is therefore indispensable to study the mechanisms involved. Besides metal alloys such as steels, materials of interest are newly developed composite materials, as well as welds [Hu 2006] and 3D-printed Ti biomaterials [Bandyopadhyay 2015, Teoh 2000], in which fatigue failure is often enhanced by substantial residual stresses.

- **Extreme conditions.** To make a realistic model and calculate an accurate safe lifetime, extreme experimental conditions are often needed. This includes high temperatures, high pressures - up to 600 bar, H2 atmospheres etc. Such conditions require thick walls of the sample container and consequently hard X-rays must be applied to probe the sample (various modes). Typical materials of interest are metal alloys and welds used in construction and engineering [Dutta 2013], Pd-alloy membranes that are applied in the energy-efficient separation of hydrogen [Uluc 2014], and materials that are to be used in future nuclear fission thorium reactors and H2 fusion reactors.

- **Self-healing materials.** Man-made engineering materials generally demonstrate excellent mechanical properties that often far exceed those of natural materials. However, unlike natural materials, man-made materials have no or very limited ability for self-healing, i.e. detect and remove or neutralize micro cracks. Currently this self-healing behaviour is investigated in many different classes of materials: polymers, metals, ceramics, concrete, composites and laminates [Zwaag 2009]. A better understanding of self-healing mechanisms can realize a revolution in the properties of the materials used in our daily lives. If fine cracks in asphalt, building materials and metals in airplanes can be repaired in an early stage, by e.g. the formation of a second phase that closes the microscopic crack, the service life will be extended considerably. In order to develop effective self-healing mechanisms, the evolution of fine cracks that are deeply embedded a metal need to be observed. In a recent experiment carried out at a Swiss synchrotron [Sloof 2016], cracks created in Ti2AlC, a so-called MAX phase, healed by an oxidation process at high temperature. The products created in this process filled the crack and created a strong bond with the crack faces. The self-healing process was monitored in situ using an X-ray tomographic setup: 3D images of the sample were acquired over time. A typical crack healing sequence, shown as 2D cuts from the 3D images, can be observed in Fig. 17. By application of phase contrast imaging in the S*L device (mode C, Fig. 7), better contrast between the repairing material and the original matrix can be obtained. Moreover, the process can be followed.

Figure 17: A crack in a self-healing material. Note that these images are 2D cuts from a 3D tomographic image that was acquired using 3D x-ray tomography.
over much longer periods, which would be in better correspondence with the average service life of these materials.

2. Corrosion – Phase contrast imaging

The economic costs of corrosion are enormous, and in The Netherlands alone estimated at 15-20 billion euros per year. This number includes the loss of metal, costs of repair and replacement, loss of functionality (including esthetical) and consequential economic losses related to inoperative machines.

The mechanisms of metal dissolution at high rates are poorly understood, but are of critical importance in localised corrosion and also areas such as electrochemical machining and electropolishing. Metal dissolution behaviour is controlled by the chemistry of highly concentrated metal salt solutions, which may be supersaturated or even contain salt crystals adjacent to the dissolving interface. Until now, the chemistry adjacent to dissolving interfaces has been extremely difficult to study, but with the development of synchrotron sources it becomes possible to study these phenomena in-situ and with high temporal and spatial resolution [Ghahari 2011]. Phase contrast imaging offers a non-destructive method that can be used to study samples immersed in water, making it an ideal method for monitoring the evolution of corrosion sites. The S*4L facility will allow studying this process over realistic timescales. A mechanistic understanding will facilitate the development of long-term predictive models of corrosion propagation for applications such as nuclear waste storage and life prediction for ageing aircraft, and will be widely applicable for understanding corrosion of, for example, biomedical prostheses or oil and gas pipelines.

The application of these techniques for more in-depth understanding of the reverse electrochemical process (i.e. electrodeposition) is indispensable as well. In the electrodeposition of metals, a widely used industrial technique, bubbles of gas generated near the cathode can adversely affect the quality of the metal coating. The bubble phenomenon has eluded experimental clarification for decades, because of a lack of probes with adequate temporal and spatial resolution and insufficient penetration to show the pattern and development of the coating in microstructural detail. Phase-contrast imaging with a high-brilliance high-energy S*4L can be used to witness directly and in real time the accumulation of zinc on hydrogen bubbles (see Fig. 18) [Tsai 2002].

Figure 18: Phase-contrast microradiographs showing the growth of zinc on hydrogen bubbles during electrodeposition [Tsai 2002].

In-situ X-ray studies on electrodegradation (corrosion) and electrodeposition (coating) would thus lead to an improved choice of materials, advance the design of new coatings and coating procedures, allow better planning of replacement works, and as a result minimize consequential losses by unexpected failures.
**Summarizing**

Above some illustrative examples have been given of research fields that would benefit greatly from Smart*Light: Medical radiology (*cardiovascular disease and osteoporosis*), humanities (*hidden text and paintings*) and materials science (*failure of materials, mitigating failure through self-healing properties*). Obviously, this collection is far from complete. Smart*Light applications extend to many other research areas. Just to name a few: protein crystallography (*medicine, viruses*), biomaterials (*hip replacement*), recycling (*extracting valuable rare earth metals*), additive manufacturing (*stresses in 3D-printed objects*) and generation and storage of sustainable energy (*solar and wind energy*).

**CHALLENGES AND RISKS**

The physical principles of Inverse Compton Scattering (ICS) have been well-established already for many decades. However this has not yet led to a compact, robust and user-friendly ICS-based alternative to synchrotron X-ray sources. In our opinion, the main obstacles which have prevented this development are twofold. First, this relates to the technological readiness-level of the components needed for Smart*Light, in particular the high-gradient X-band accelerator, the pulsed laser and the low-emittance electron gun. These critical components have become available only recently as reliable, off-the-shelf products. That is why Smart*Light is now within reach. Second, efforts in the past have taken a somewhat isolated and fragmented approach in terms of project partners. In Smart*Light we bring together academic partners of all relevant disciplines, both from an instrumental and a user perspective. What is more, we also have relevant industrial partners on board, including VDL-ETG, PANalytical, and CERN spin-off ASI. Their involvement will be crucial in reaching our final goal: a user-friendly, reliable and accessible ICS-based alternative to synchrotron sources. A strong point of Smart*Light is that project partners are all from The Netherlands.

**Technical challenges**

The main technical challenge is stable alignment of the colliding micron-sized electron and laser beams in the interaction point. This will require advanced diagnostic methods and extremely stable mechanical design, preferably with active control. The Eindhoven group has the required expertise with beam diagnostics. For stable mechanical design and active control expertise will be provided by VDL-ETG and the High Tech Systems Center (HTSC) at TU/e.

A major advantage of the proposed facility is the possibility to rapidly change X-ray energy and beam divergence. Changes in energy and/or divergence require however entirely different settings of the accelerator components, in particular the (minimally) 8 current settings of the focusing magnets (see Fig. 6). Automatic adjustment procedures have to be developed, along with monitoring by a multitude of diagnostic elements to enable active control.

An important challenge is the improvement of hard X-ray detection efficiency and temporal resolution, which is under development in the research labs of consortium partner ASI. Finally, deceleration LINACs would be highly desirable to minimize shielding requirements. This will require a careful design with continuous radiation monitoring and fast shut-down procedures in case of beam failure.

**Organizational risks**

Besides the technical challenges in realizing Smart*light, we see two main organizational risks. First, this relates to the great variety of our consortium with diverse interests, different disciplinary backgrounds and from various societal sectors. That is why Smart*light needs a strong project leader, who has the ability to unify all interests and prevent the project from disintegrating into multidisciplinary actions. Second, we see a concrete risk that a lab-scale, proof-of-principle system is realized, but not taken further to a robust, consolidated demonstrator that will convince the different user-communities to stay on board. For this reason we think it is crucial to also have industry durably involved, such that finally a commercial system is made available. This is essential if the technology is to be made available on a much wider scale.

A big challenge will be securing the funding for all subsequent development steps. This has to include fundamental academic funding in the initial stage, but also funding for technology transfer as the technology matures.
## B. Embedding

### How does the proposal fit into the (international) landscape of large-scale research facilities?

The main idea of Smart*Light is to bring advanced, large-scale analytical capabilities to the laboratory, rather than the other way around. In that sense our plan deviates from single-site research infrastructure. We have shown the scientific working principle of Smart*light and its potential use for three different user communities, i.e. the medical field, materials science and cultural heritage studies. Note that this list is not exhaustive. We see ample possibilities for other user communities to join Smart*light, including fields like mineralogy, protein crystallography and other fields from the life sciences. The access to Smart*light will have to be enabled through close collaboration with the three core user fields defined above. In a later stage, when the first on-site demonstrator of Smart*light is available we will actively disclose partners from other disciplines.

### What is the connection to existing facilities?

NWO subsidizes the DUBBLE synchrotron facility at the ESRF in Grenoble, which is specialized in high-quality SAXS/WAXS and EXAFS experiments at energies in the 10 keV range. For all situations given in this proposal, neither the DUBBLE beamline nor other SR beamlines would provide a suitable alternative. Conversely, Smart*Light will not by any means provide an alternative to a specialized facility as DUBBLE. Firstly, the brilliance in the 10 keV range suitable for SAXS/WAXS and EXAFS is orders of magnitude higher in synchrotron facilities, and secondly, the full infrastructure of DUBBLE is extremely well-developed and too specialized to transfer to a table-top facility. The proposed facility will be unique and can as such provide an addition to the successful DUBBLE beamlines, considering that a growing interest exists in high-intensity X-rays, and specifically in techniques that will be enabled with Smart*Light. The Smart*Light facility will benefit from the existing knowledge at DUBBLE.

### Are there any comparable ideas, proposals or already existing facilities abroad? If so, what does it mean for the Smart*Light proposal?

Presently there are several ICS X-ray source initiatives worldwide, with similar aims and applications:

- The commercial Lyncean system [Lyncean], developed 10 years ago at Stanford University. A single system has been sold and is operational now at TU Munich, with main application PCI for life sciences. The Lyncean system is relatively compact and based on the combination of a LINAC and a storage ring. As a result the coherence and brilliance are not sufficiently high to compete with SR sources. In addition, changing the X-ray energy takes many hours and a lot of concrete shielding is required. The Smart*Light system should perform much better.

- The French ThomX project [Bruni 2010]; a demonstrator project, also based on the combination of a LINAC and a storage ring, which is currently under construction. The ThomX system is not a compact facility, requiring a shielded large-accelerator environment, which makes it much less suitable for in situ operation than the Smart*Light setup. Moreover, the use of a storage ring makes it less flexible in operation. Applications: cultural heritage and medical science.

- The Compact X-ray Light Source (CXLS) [Graves 2014]; the CXLS proposal (MIT, Stanford) is very similar to Smart*Light, based on X-band LINACs. CXLS has secured funding and will take off in 2018 at Arizona State University in the US. This is the most serious competition. A particular important advantage of the Smart*Light consortium over CXLS is its close connection to CERN and the specific involvement of VDL-ETG, which gives access to state-of-the-art X-band technology. More generally, the strength of Smart*Light which sets it apart from other ICS X-ray source initiatives worldwide, is the involvement of experts from all required disciplines, in a unique collaboration between TU Delft, TU Eindhoven, U Twente,
CERN and Dutch high-tech companies VDL-ETG, PANalytical and ASI.

- **How does the proposal fit with Dutch research strengths?**

This proposal dovetails seamlessly with existing research strengths in the Netherlands. On the one hand this concerns the instrumental partners that will be responsible for building Smart*light. We bring together cutting-edge expertise in accelerator physics (TU Eindhoven), laser optics (U Twente) and X-ray detector development (ASI). One the other hand, also the user communities are prominent academic players. Medical diagnostics (Erasmus U), the cultural heritage field (TU Delft & museum partners) and materials science (TU Delft) have a strong international reputation. Note that all team members are at the international academic forefront in their respective disciplines, but also bring in highly relevant industrial partners. This proposal aims to bring these strengths together, by the joint development and application of a new generation of X-ray sources.

Smart*Light connects the following existing strongpoints of The Netherlands:

- Collaboration of all technical universities (3TU);
- Excellent chances for valorisation through the ‘topsector’ High-Tech Systems and Materials (HTSM);
- Connection with NICAS, the Netherlands Institute for Conservation, Art and Science, given special attention by the Dutch cabinet in the "Ikoonproject 2015" contest;
- Connection with Medical Delta, a collaboration of Leiden, Erasmus and Delft in the field of medical technology;
- Direct interface with the Nederlandse Wetenschapsagenda (NWA), in which high-tech development, medicine, materials and the arts are highly prominent ‘exemplary routes’ for academic research in the 21st century.

- **Describe how the Dutch research culture will benefit from the realization of the facility.**

This proposal has a strong academic profile, while also serving societal and economic demands on the long term. We will open up new academic vistas in X-ray based research and subsequently offer exciting chances for economic and societal valorisation. What is more, our proposal bridges all domains of the new organisation of NWO: Social Sciences and Humanities (SSH), Applied Technological Sciences (TTW), Medical Sciences (ZonMW) and the Natural Sciences (Beta). This makes Smart*Light an ideal program to be worked out in the framework of NWO, which aims to strengthen such multidisciplinary programs in the years ahead. Dutch research culture is known for its efficient communication across the disciplines. When also considering the domestic industrial network, the Netherlands are a perfect platform to bring Smart*Light to fruition.

**C. ORGANISATION AND FINANCE**

**Organisation**

This project will be carried out in 4 phases over the next decade:

**Phase 1 (2016-2017)** - securing successful financial and organisational strategy for Smart*Light

- identifying potential funding possibilities from various sources, including NWO, ministry of economic affairs, 3TU, individual university boards, and potentially private partners
- recruiting a professional project leader for Smart*Light

**Phase 2 (2017-2019)** - building the Academic Prototype of Smart*Light

- delivering experimental proof-of-principle of beam characterized in this proposal
- carrying out feasibility studies for user communities, location: TU Eindhoven (Luiten)

**Phase 3 (2018-2022)** - building the Application Demonstrator of Smart*Light for user communities

- realizing a robust, consolidated application demonstrator for in-situ use
- making research mileage in one or more user areas defined in this proposal
Phase 4 (2022-2025) - Technology Accessibility and Diffusion

- Disclosing additional user communities
- Interfacing with industry to safeguard technology distribution

Finance (rough cost estimates)

- **Phase 1 (2016-2017):** no funding required.
- **Phase 2 (2017-2019):** for the realisation of an Academic Prototype in Eindhoven we need to hire a project leader and experts in the three disciplines accelerators, lasers and X-rays. Two specialists per discipline and a project leader for three years amounts to approximately 2 M€. For the purchase of specialized equipment (high-power pulsed laser: 0.5 M€; X-band klystron and modulator: 1 M€; X-band RF equipment and accelerator structures: 0.5 M€; mechanical design and construction, beam diagnostics, high power laser optics, consumables, etc.: 0.5 M€) we estimate 2-3 M€ is needed. **Total estimated cost:** 5 M€.
- **Phase 3 (2018-2022):** building the Application Demonstrator in Delft will require a similar investment. **Total estimated cost:** 5 M€.
- **Phase 4 (2022-2025):** in this phase we expect industry to take over; no additional funding required.

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<th>Acronym</th>
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<td>XRF</td>
<td>X-Ray Fluorescence</td>
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