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Proposal

High Frame Rate Fast-Neutron Radiography

instrument

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Contents

Summary

Neutron radiography is a well-established technique. However, fast-neutron radiography is relatively new and unexplored, although several advantages are manifest. High frame rate opens up the possibility to measure fast dynamic processes, without the need for time averaging and the loss of spatial resolution. In this report a proposal is given for the realisation of combination of a high frame rate and fast-neutron radiography instrument.

Specific advantages for the instrument are:

- *A high frame rate* realised by the use of an intense pulsed neutron source created by an accelerator facilitating the investigation of dynamic processes.
- *Neutron-energy selection* by means of time of flight facilitating resonance energy contrast variation.
- *Optional horizontal or vertical illumination* of a sample by means of an adjustable neutron source position.
- *Tomography* realised by multiple neutron source positions.

Numerous application examples are described in high frame rate, slow frame rate or static mode showing the potential of the proposed instrument.

Finally the economic feasibility is calculated, showing the costs and benefits of the instrument during the realisation, exploitation and dismantling.

1. Introduction

Radiography has its roots in the pioneering discovery of Röntgen who, in 1895, obtained a radiographic image using a high-voltage vacuum tube and fluorescent screen. The implications of this discovery of X-rays were soon employed in medical diagnosis and, in due course, a new domain of medical practice emerged. Subsequently X-rays were used as a probe for the study of fundamental properties of matter and as an inspection tool of manufactured products. The eventual availability of γ-ray sources provided a further expansion of diagnostic uses of electromagnetic radiation.

It was Chadwick's discovery of the neutron in 1932 that led to important new directions in science and technology. Unlike X-rays and γ-rays, neutron interaction is due to nuclear rather than electronic characteristics of the medium through which it passes.

Kallman provided the first experimental demonstration that neutrons were of radiographic relevance in the 1940's. The actual developments of neutron radiographic applications was only realised after the development of sufficiently intense neutron beams becoming available with the development of research reactors in the 1950's and 60's.

By now, static thermal-neutron radiography is a well-established technique in use for many different applications.

However, for fast-neutron radiography this is different. At several institutes in the world fast-neutron radiography is being developed. At Lawrence Livermore National Laboratory in the USA [2] experimental studies are performed on the feasibility of fast-neutron radiography. Time-of-flight fast-neutron radiography is considered in Germany [3] and resonance fast-neutron radiography is realised in South Africa for an industrial application [4]. High frame rate thermal-neutron radiography is realised in Japan [5]. Other institutes are doing preliminary studies also [6-9], but unto this day no *high frame rate fast-neutron* radiography instrument was considered.

2. Description of instrument

Here, only the principle, special features and instrument set-up are described. More details about the actual parameters can be found in the report on the technical feasibility of a high frame rate fast-neutron radiography instrument [1].

2.1 Principle

Neutron radiography involves three components (see figure 2.1):

a) a suitable neutron beam,
b) an object of radiographic interest,
c) a detector, i.e. a device to record the radiation intensity information associated with the neutron beam transmitted through the object.

Nuclear fission reactors most commonly supply neutron beams. Accelerators and radioisotopes can provide alternative neutron sources. The important considerations involve the intensity of the neutron source, the spectrum of neutron energies, the collimation of the neutron beam and its time structure.

As neutrons pass through an object, they interact with nuclei by scattering and absorption. The probability of such events is an isotopic property and accounts for the unique radiographic information available with neutron beams. Fundamental beam interaction considerations suggest that the fractional decrease in a neutron beam per unit distance in the beam direction is a constant for the absorption and / or scattering process. The number of neutrons absorbed and / or scattered is proportional to the number of neutrons present and to the extent of the absorbing and / or scattering domain.

Since neutrons constitute a non-ionising form of radiation a converter is needed to create a particle that can be recorded by a photographic film, a photomultilpier tube, a CCD or an other kind of detector. The important considerations here are image resolution, detector efficiency and the time needed for the detector to convert a neutron into a usable signal.

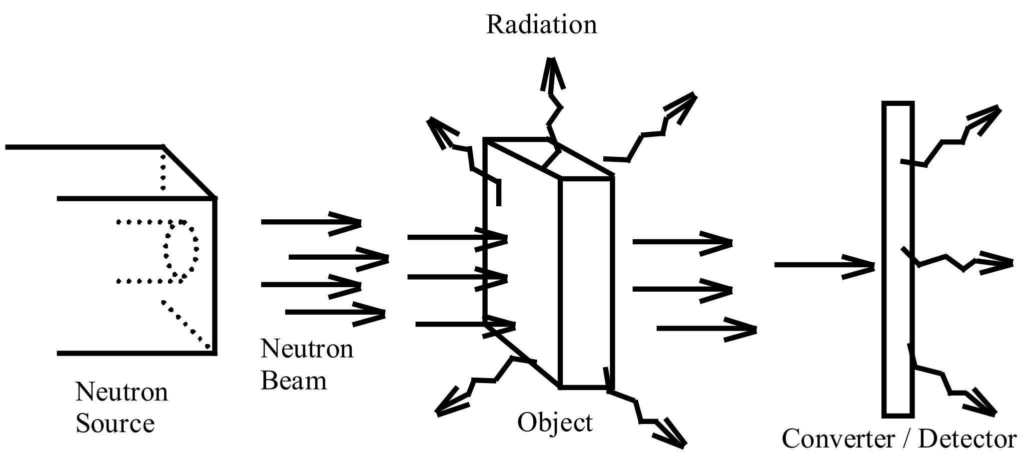

Figure 2.1: *Graphical depiction of neutron radiography.*

2.2 Special features

2.2.1 Fast neutrons

Fast neutrons are used because of their unique material penetrating properties and their relatively high source strength at which they can be made available. Typical the absorption of X-rays is proportional to the number of electrons present, while the absorption of thermal neutrons varies rapidly from isotope to isotope, enabling the use of isotopic substitution to enhance the contrast. The total macroscopic cross section for fast neutrons is less than its thermal-neutron counter part, thus enabling a larger penetration depth. Another advantage of fast-neutron radiography is the use of resonant features of the scattering cross sections. The total microscopic cross section of most isotopes is strongly dependent on the neutron energy. Hence, by changing the energy of the neutron beam or selecting neutrons within a certain energy range, it is possible to enhance or reduce the contrast between different materials in the object. Another way to enhance the contrast is by adding a neutron absorbing material to the object.

2.2.2 Time of flight

Time of flight can be used to select neutrons of a certain energy range. After fast neutrons are created in the source, some of them will travel towards the detector with a certain speed. The time of flight is the time needed by the neutrons to cover the flight path between source and detector. The neutrons will reach the detector at a time dependent on their energy. This enables the determination of the neutron energy by recording the detection time and the creation time. In this way energy selection of the neutrons can be accomplished. This further facilitates the reduction of background due to the detection of γ-rays created along with the fast neutrons. γ-rays travel at the speed of light and reach the detector after a time, which is considerably faster than the fastest neutrons considered here.

2.2.3 High frame rate

The frame rate is the frequency at which radiographic images are taken. A high frame rate is needed to be able to study fast time-dependent phenomena. This accounts for the need of a bright fast-neutron source. For instance an exposure time of maximal 1 ms is allowed to be able to investigate flow properties of a two-phase flow with a (moderate) speed of 1 m/s with a resolution of 1 mm. To be able to investigate the continuous time dependence of this flow a frame rate of 1000 Hz is needed. However, the important parameter here is the exposure time of 1 ms needed to obtain sharp pictures. The time between pictures need not be zero, but can be larger depending on the type of flow considered. A duty cycle down to 10 % seems reasonable, giving the possibility of increased neutron flux during exposure time by pulsed operation of the source and time for data acquisition between exposures for instance read out and storage of the obtained image.

2.2.4 Dynamical mode

If a motion is repetitive or cyclic (for instance pumps or engines) it is possible to enhance the quality of the radiographic image by averaging multiple short exposed images. Effectively the number of exposed images taken multiplied by the single-exposure time will increase the exposure time. In this way the resolution degradation due to the motion of the object can be reduced, while maintaining the contrast capabilities of a longer exposure time.

2.2.5 Tomography

Although 2D information of an object is an important source of information on the object properties, sometimes it is necessary to obtain 3D tomographical information. Lateral information is obtained by contrast variation. Longitudinal information can be obtained by stereoscopic vision. The longitudinal information needs a resolution comparable to the lateral resolution. Therefore, the angle between the stereoscopic images must be large, in which case it is more convenient to add another detector. A normal way to achieve this is to rotate the object over 90^o. However, for time dependent measurements it is not possible to rotate the object. Here it is needed that both source-detector combinations are measured at the same time or at alternating time intervals smaller than the time interval of interest. Hence, two neutron sources are needed. This can be realised by use of an accelerator. The accelerated beam can be alternated targeted on two fast-neutron creating targets at positions resulting in two mutual perpendicular neutron beams on the object.

2.3 Set-up, available systems and development

In view of the instrument considered here a construction is proposed meeting the following criteria:

a) The instrument must be capable to implement the features as discussed in previous paragraphs.
b) As many parts as possible of the instrument must be bought from suppliers that have proven their applications meet their specifications. All other parts must be available without any major technological risks, ensuring the realisation of the instrument.
c) Adaptation of the instrument to different requirements should be possible.
d) The object under investigation must be changed relatively easy and rapid.

A top view of a possible set-up for the instrument is shown in figure 2.2. Notice the special configuration to enable tomography. The deuteron beam is directed alternating to the upper and lower target. Before the target is hit by the deuterons the beam is rotated for 90^o, because the neutron yield in the forward direction is largest. Neutrons are thus alternating created in the upper and lower target, travelling through the object and converted in the imaging systems. Further a massive high-quality shielding is applied to reduce the radiation exposure.

The intention is to buy as many parts as possible from suppliers. The accelerator, beam handling, object positioning, scintillator and imaging systems can be bought from suppliers directly as standard parts or modification of standard parts. Some special parts of the instrument are not (readily) available from suppliers (without excessive costs) and must be developed:

Rotating target

The target must be able to produce as many neutrons per second as possible. A problem is the associated heat production, which is proportional to the number of created neutrons per second. Although several designs are considered, there is still not a standard rotating target for fast-neutron radiography available.

Imaging system and fast-neutron detector

The neutron source in combination with a parabolic mirror proposed here enables the use of a thicker converter without loss of resolution. A thicker converter increases the detection efficiency of the fast-neutrons. A better detection efficiency reduces the number of fast neutrons needed to obtain an image with a certain quality. The result is an increased performance of the instrument or a reduced radiation dose for the object under investigation.

Time-of-flight radiography

Time of flight enables energy selection of the neutrons and discrimination of γ-radiation or thermal neutrons. The first feature enables contrast enhancement or resonance radiography. The second feature reduces the background countrate resulting in a better signal-to-noise ratio. Time-of-flight fast-neutron radiography has been proposed and tested, but no instrument is available unto this day.

Finally, the shielding, electronics and firm- and software must be designed, constructed and tested as part of the project.

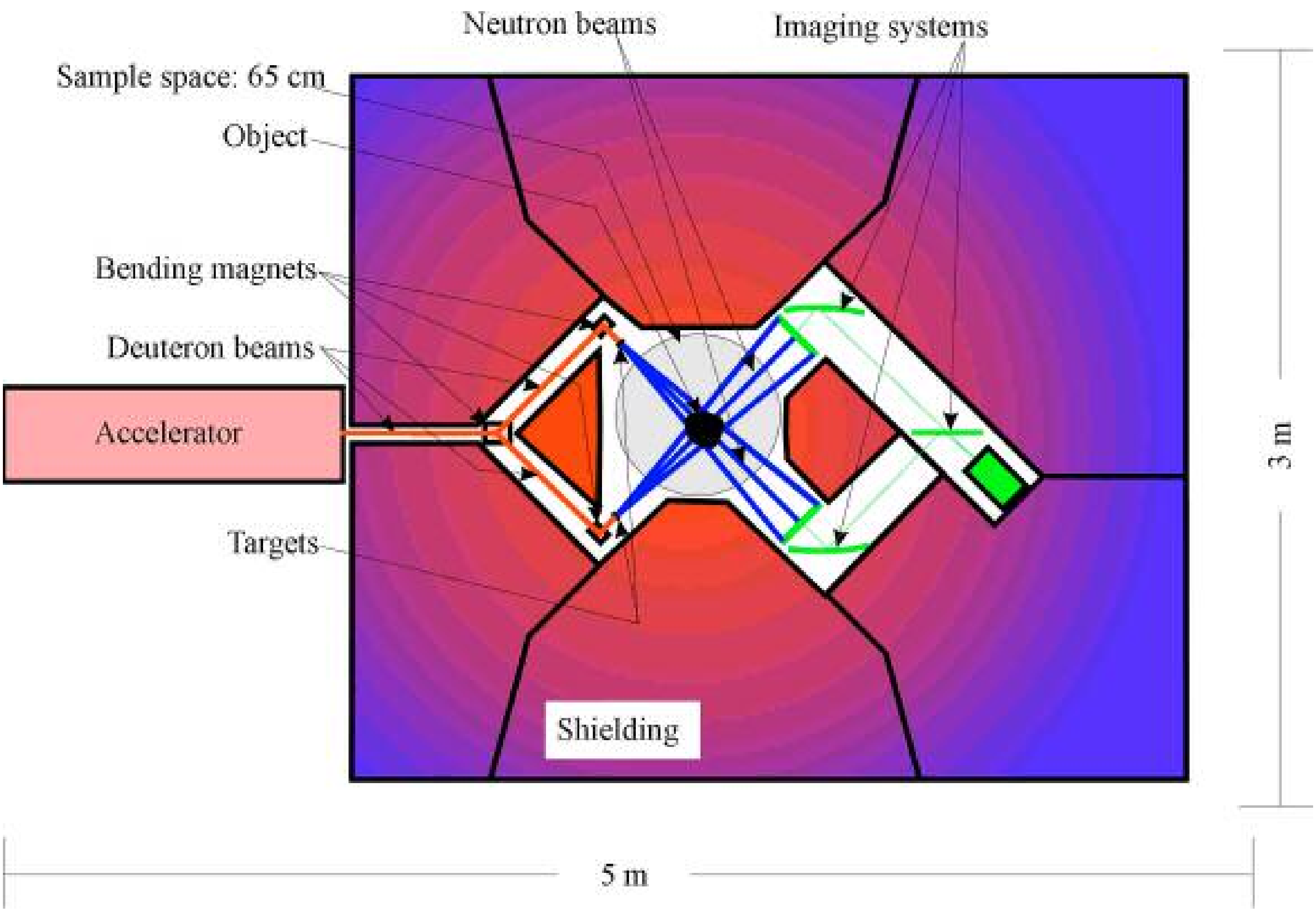

Figure 2.2: *Schematic set-up for a high frame rate fast-neutron radiography instrument.*

3. Application examples

Applications for the proposed instrument can be grouped into several categories. A category is basic research and another is industrial applications. Another grouping is the mode the instrument could be used in. A high frame rate fast-neutron radiography instrument can also be used in a low frame rate or static mode. This opens possibilities for enhanced resolution and/or contrast of the images, resulting in different research areas. Sometimes an application could be mentioned in several categories. However for the sake of transparency this is omitted. First, examples of applications for the high frame rate mode of the instrument are discussed. Second, examples of applications for the low frame rate of static mode. Finally, the possibilities for potential spin-off are discussed.

3.1 High frame rate fast-neutron radiography

3.1.1 Basic Research

Two-phase flow

Although two-phase flow has important technological and industrial applications it is a wide and relatively unexplored area of research. Gas-liquid two-phase flow is used in heat exchangers like refrigerators and boilers. An example is a steam generator for liquid metal fast reactors using liquid-liquid direct contact heat transfer between liquid metal and water [10]. Since liquid metals are opaque to standard optical rays, it is impossible to visualise and measure flow fields of a liquid metal by optical means. Gas-solid two-phase flow is used in fluidised beds. An example is the development of a fluidised bed for coal and/or incineration firing to reduce emissions such as NO_x and/or SO_x to the environment [11]. Again, since the container and the bed are opaque to optical rays, it is impossible to visualise and measure flow fields by optical means. Because of the difficulty of performing quantitative measurements, the theory of two-phase flow and model validation is a vastly unexplored territory. Historically, pioneering work on two-phase flow quantitative measurements by thermal-neutron radiography was performed by Mishima et al. [12-14]. This work opened up a way to application of neutron radiography to visualisation and quantitative measurement of these thermal hydraulic phenomena. Quantitative measurements can be done by applying image-processing techniques to the consecutive pictures taken. However, by the use of thermal neutrons the penetration depth and hence dimensions of the objects under investigations are limited. Fast-neutrons can be used to increase these parameters. Further the dynamic properties of the two-phase flow can be studied using a high frame rate.

Steam explosion

A steam explosion can occur when there is a direct liquid-to-liquid or liquid-to-solid contact with a large temperature difference. In a severe accident of a nuclear reactor, a steam explosion may occur due to the direct contact of molten core and coolant, resulting in an explosive pressure wave. This wave may destroy the containment and as a consequence fission products may be released into the atmosphere. Although the condition to initiate a steam explosion has been studied extensively, the process of steam explosion has not been studied well. Recently visualisation techniques using X-rays and thermal neutrons were applied to the investigations on the behaviour of molten metal inside a steam bubble [15]. High frame rate fast-neutron radiography could contribute to this field by being able to measure through thicker samples with a short exposure time.

3.1.2 Industrial Applications

Combustion engine fluid dynamics
The dynamic distribution of combustion engine fluids becomes more important when the performance of the engine is enhanced. Hence, the need for visualisation and quantification of these fluid dynamics [16]. For these dynamic visualisation short exposure times and large penetration depth are advantageous.

Fluidised beds (steel industry)
The movement of bed material in a fluidised bed is important for the heat exchange properties of a fluidised-bed heat exchanger. Visualisation and quantitative methods are desired but limited due to the characteristics of the materials used. Neutrons can be used to overcome these problems. Especially fast-neutrons for they have strong penetrating properties [17].

Two-phase flow (petrochemical industry)
The study of two-phase flow is also important for the petrochemical industry. Possible applications are the investigations of turbulent oil-gas flow through a pipe.

3.2 Fast-neutron radiography

3.2.1 Basic Research

Water transport in porous building materials
Non-destructive monitoring of capillary processes is important in view of the degradation of building materials due to repetitive freezing and melting of water inside these materials. With neutron radiography the water content of materials can be visualised and quantified without destroying the sample. Further, with fast-neutrons thicker objects can be investigated reducing the influence of sample preparation methods [18,19].

Transport and distribution of liquids in materials and soils
Non-destructive monitoring of capillary processes is important in view of the dynamics of liquids in materials and soils. With neutron radiography the liquid content of materials and soils can be visualised and quantified without destroying the sample. Further, with fast-neutrons thicker objects can be investigated reducing the influence of sample preparation methods.

3.2.2 Industrial Applications

Quality control
As any visualisation technique fast-neutron radiography can be used for quality control. As the internal structure of the material is revealed, it can be used for quality assessment. When thick samples must be investigated fast-neutron radiography can be an important tool.

Composite materials testing
Composite materials are built out of many layers of different materials connected to each other by means of an adhesive. The distributions of these components can be in-situ investigated by means of radiography. Possibilities for fast-neutron radiography are for materials that are thick or have too little contrast with X-ray or thermal-neutron radiography.

Nuclear fuel inspection
Nuclear fuel consists of heavy elements reducing the contrast of X-ray or thermal-neutron radiography. Further, thermal-neutrons tend to induce radioactive reactions reducing the image qualities. To overcome these problems fast-neutrons can be used.

Geology
To investigate thick rock samples for the presence of inclusions, fast-neutron resonance radiography can be used. By subtracting the image taken off-resonance from the image taken on-resonance it is possible to determine the position, size and number of inclusions. This can be applied to diamonds is rocks, which for X-ray or thermal-neutron radiography have a very small contrast.

3.2.3 Irradiation

Isotopes can be produced by radiating an appropriate target with either the deuteron beam directly from the accelerator or the fast-neutrons produced by the target.

3.3 Spin-off examples

Every new development renders spin-off. Spin-off resulting in new skills or spin-off in view of offering (part of) the new skills as techniques available to others. For the instrument considered here several spin-offs are possible.

Explosive detection system and security applications
Many techniques have been proposed to detect explosives and contraband in luggage and containers. The fundamental requirements are those of penetrability for large objects, sensitivity and specificity. Hence, the possibility to use fast-neutron radiography. With fast-neutron resonance radiography a 2-D elemental mapping of hydrogen, carbon, nitrogen, oxygen and the sum of other elements can be obtained from images taken at different neutron energies chosen to cover the resonance cross section features from one or more elements. With this technique it is possible to detect the position of explosive in luggage and containers [8,20-24].

Boron Neutron Capture therapy
The neutron-producing principle using an accelerated beam of particle impinging on a target can also be used to produce an epi-thermal neutron beam, which can be used by the boron neutron capture therapy [25]. This therapy enables the selective irradiation of cancer cells preventing unwanted radiation damage to healthy tissue. If this therapy can be made available at hospitals this would greatly enhance the applicability of the method.

4. Economic feasibility

In the following paragraphs the economic feasibility of the proposed instrument is described. Three main phases can be distinguished: The realisation phase, the exploitation phase and the dismantling phase. The realisation phase consists of all that is needed to construct a working instrument, except the accommodation costs for the instrument. The same holds for the exploitation phase: the accommodation and infrastructure needed to operate the instrument are not taken into account. However, the costs for operation itself are taken into account. The dismantling phase consists of all that is needed to dismantle the instrument. Main costs here are assumed to be the cooling down of the irradiated materials and the possible disposal of it as (low-radioactive) nuclear waste.

4.1 Costs and benefits during realisation

Costs depend on the precise properties of the instrument. These are described in [1]. Dependent on these properties a minimum and maximum of costs of the different parts can be calculated. Besides these costs there are also expenses for project management. An overview of these costs is shown in table 4.1. Besides costs there are also benefits during the realisation of the instrument. Some parts of the instrument are new and can be published. Further a combination of several existing techniques is also new and can be published too. These benefits are shown in table 4.2. Except for these obvious benefits there are also benefits which are much more difficult to translate into financial terms. These include the gain of esteem from the national and international community for the acquired skills.

4.2 Costs and benefits during exploitation

For the economic feasibility the exploitation of the instrument is crucial. What part of the investment will be returned as benefits during the lifetime of the instrument? Several benefits can be quantified such as the number of publications it produces. The use of the instrument by industry is another benefit. Education of students is more difficult to quantify, but an important benefit. Further, there are possibilities for spin-off. Realisation of the instrument can trigger the development of (mobile) systems for detection of explosives or radiation of cancer patients. However, these spin-off benefits are not taken into account. During exploitation of the instrument there will be costs associated with maintenance and use of the instruments. Table 4.3 gives an estimation of the costs and benefits during exploitation.

	Minimum	Maximum	Project Management
Accelerator	**2000**	**3000**	**40**
Beam manipulation	**250**	**500**	**10**
Target	**200**	**300**	**58**
Object positioning			
Translate	**10**	**20**	**1**
Rotate	**30**	**50**	**1**
Detector			
Scintillator	**5**	**10**	**1**
Imaging system			
Parabolic mirror	**50**	**100**	**3**
Lens	**10**	**20**	**1**
Image intensifier	**50**	**100**	**1**
CCD	**90**	**190**	**2**
Holder	**50**	**100**	**10**
Shielding	**250**	**500**	**25**
Further constructions	**100**	**200**	**25**
Timing electronics	**100**	**200**	**50**
Computer hardware	**50**	**75**	**1**
Computer software			
Control	**50**	**100**	**5**
Data reduction	**50**	**100**	**5**
Imaging	**25**	**50**	**5**
Sub total	**3370**	**5615**	**244**
Unforeseen 10 %	**337**	**562**	**24**
Total	**3707**	**6177**	**268**

Table 4.1. *Minimum and maximum costs realisation and project management (keuro).*

	Costs	Benefits
Target	**2**	**20**
Detector		
Imaging system		
Parabolic mirror	**2**	**20**
Time of flight	**2**	**20**
High frame rate	**2**	**20**
Total instrument	**2**	**20**
Others	**10**	**100**
Total	20	200
Net		180

Table 4.2. *Net benefits publications realisation instrument (keuro).*

	Costs	Benefits
Instrument maintenance	**50**	
Instrument use (1/2 fte)	**20**	
Research (2 fte)	**80**	
Publications (5 per year)		**100**
Promotion (1 per 2 years)		**25**
Education		**100**
Use by third parties		**93**
Writing off	**168**	
Total	**318**	**318**

Table 4.3. *Exploitation budget (keuro per year).*

Accelerator	**10**
Beam manipulation	**5**
Target	**1**
Shielding	**23**
Further constructions	**10**
Sub total	**59**
Unforeseen 10 %	**6**
Total	**65**

Table 4.4. *Costs dismantling (keuro).*

	Costs Minimum	Costs Maximum	Benefits Minimum	Benefits Maximum
Realisation	**3707**	**6177**		
Project management	**268**	**268**		
Publications			**180**	**180**
Exploitation benefits during lifetime			**2688**	**2688**
Dismantling	**63**	**63**		
Subsidies (IRI, TUD, STW, industry)			**1170**	**3640**
Total	**4038**	**6508**	**4038**	**6508**

Table 4.5. *Total budget (keuro).*

4.3 Costs during dismantling

For the economic feasibility the dismantling of the instrument is mostly a forgotten item. However it can mount up to a fair amount if it is not considered in the design of the instrument. Especially when there is a possibility of the creation of radioactive materials.
Table 4.4 gives an estimation of the costs and benefits during dismantling.

4.4 Budget

Table 4.5 shows an overview of the total costs, benefits and subsidies needed for the project. For the economic lifetime of the instrument 16 years is used. After this time it is assumed that the technique has become redundant, the instrument worn or its usefulness reduced to zero. Total costs for the instrument are estimated to be about 4 – 6.5 Meuro. In its 16-year lifetime it is estimated that 2.688 Meuro will be returned by publications, promotions, education and research by third parties. Publications associated with the realisation of the instrument result in a net benefit of 0.18 Meuro. The difference between costs and benefits must be financed by subsidies by government and/or sponsoring by industry. When the costs increase the subsidies by government and/or sponsoring by industry must be enlarged. Total investment by IRI is at least 2.805 Meuro, which will be returned during the lifetime of the instrument.

5. Conclusions

This proposal shows that high frame rate fast-neutron radiography is both technical and economical feasible. Furthermore, fast-neutron radiography and high frame rate radiography are new techniques, which are currently developed at several places in the world. The combination of high frame rate and fast-neutron radiography is unique unto this day. The use of time of flight technique and multiple neutron sources gives the instrument even more powerful characteristics, enabling elemental imaging and tomography.

The potential of the new instrument is shown in the examples of the applications. It is shown that besides the high frame rate mode there are also applications in the slow frame rate or static mode. The spin-off of the instrument development can be considerable.

The total costs for the realisation of the instrument varies between 4.0 and 6.5 Meuro dependent only on the required performance of the instrument, excluding the accommodation costs. The maximum return on investment is calculated by translating the actual benefits into financial benefits. In total the maximum return is calculated to be about 2.8 Meuro during the instrumental lifetime of 16 years. To cover all costs the total needed subsidy varies between 1.2 and 3.6 Meuro.

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