Business plan for a 3-TU Centre of Excellence:

Multiscale Phenomena in Fluids and Solids

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1 Contacts

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2 Participating groups and scientific challenges

The Dutch Fluid and Solid Mechanics is a traditionally very strong field and internationally well recognized.

At university level the Dutch Fluid and Solid Mechanics community is organized within two well established inter-university Research (Graduate) Schools, namely, the J.M. Burgers Centre for Fluid Mechanics (abbreviated JMBC) and the Engineering Mechanics School for Solid Mechanics (abbreviated EM). The collection of these Graduate Schools is defined to be the Centre of Competence.
The participating groups per university are summarized in the table on the next page.

Delft University of Technology

Professor	Group	Fte staff / group
Profs Westerweel/Hunt/Ooms	Fluid mechanics	6.2
Colonna (Prof. Spliethof)	Energy technology	0.8
Profs Pinkster/ van Terwisga	Marine Technology	1.
Prof. Wesseling	Numerical Analysis	3.0
Prof. Hermans	Mathematical Physics	0.2
Prof. Heemink	Applied Mathematical Analysis	1.9
Profs v.d. Akker / Kleijn / Mudde / Oliemans / Roekaerts	Multiscale Physics	9.0
Prof. v.d. Hagen	Physics of Nuclear Reactors	0.7
Prof. Coppens	Chemical Technology	0.7
Prof. Schmidt-Ott	Particle Technology	0.8
Profs Bakker / Koren	Aerodynamics	2.6
Profs Stelling/Battjes	Environmental Fluid Mechanics	4.2
Prof. de Borst	Engineering Mechanics	3.4
Prof. Gürdal	Aerospace Structures	1.4
Prof. van Keulen	Optimization and Computational Mechanics	1.0
Profs Ernst / Rixen	Mechanics of Materials	2.2
Prof. Sluys	Computation. & Struct. Mechanics and Dynamics	2.0

Eindhoven University of Technology

Professor	Group	Fte staff / group
Prof. van Dongen	Gas Dynamics/ Aeroacoustics	1.0
Profs. van Heijst / Kelder	Vortex Dynamics and Turbulence	4.2
Profs. de Goey / Baert / Aldén	Combustion Technology	5.6
Prof. Brouwers	Process Technology	1.2
Prof. van Steenhoven	Energy Technology	3.8
Prof. van Duijn	Applied Analysis	2.1
Prof. de Waele	Low Temperat. Physics and Techn.	1.2
Profs Nijmeijer / Rooda / Steinbuch / van Campen	Systems, Dynamics and Control	4.0
Profs Baaijens / Geers / Dietzel	Materials Technology	3.0
Profs Mattheij / de Graaf	Analysis, Scientific Computing and Applications	2.5

2 Participating groups and scientific challenges

University of Twente

Professor	Group	Fte staff / group
Prof. Kuipers	Fundamentals of Chemical Reaction Engineering	1.5
Profs Briels/Slot	Mesoscale Physics/Rheology	2.4
Profs Lohse / Prosperetti	Physics of Fluids	9.3
Profs Mugele / Brady	Micro Fluid Dynamics	4.2
Profs van Groesen / Molenaar	Applied Analysis & Mathematical Physics	1.3
Prof. van der Vegt / Clercx / Geurts	Numerical Analysis & Computational Mechanics	3.6
Profs Hoeijmakers / Hirschberg / Schnerr	Engineering Fluid Dynamics	2.0
Prof. van der Meer	Thermal Engineering	0.8
Prof. Hulscher	Water Engng and Management	5.3
Profs. de Boer / Huétink	Applied Mechanics	2.2
Prof. Schipper	Surface Technology & Tribology	0.6
Prof. Jonker	Mechanical Automation	0.6
Prof. Akkerman	Production Technology	0.8

RUG

Professor	Group	Fte staff / group
Prof. Levinsky	Combustion Science and Engng	3.5
Prof. Veldman	Comp. Mech. and Num. Math.	3.5

RUN

Professor	Group	Fte staff / group
Profs ter Meulen / v.d. Water	Applied Molecular Physics	2.4

UL

Professor	Group	Fte staff / group
Prof. van Saarloos	Theoretical Fluid Mechanics	1.7

Counting rules:
1 full-time professor _ 0.3 fte (JMBC) or 0.4 fte (EM) for research
1 full-time U(H)D _ 0.4 fte for research
1 full-time post-doc _ 1.0 fte for research
PhD students have not been taken into account

As can be seen from the above survey, the Centre of Competence also embraces a small number of groups from outside the 3-TU.

From the point of view of the Centre of Competence the most urgent and challenging problems in the fluid and solid mechanics of the 21st century are complex fluids, turbulence, micro- and nanofluidics, the prediction of structural mechanical behavior from the material properties, nonlinear dynamics, tailoring/optimization of mechanical behavior, fluid-structure interaction, and solver efficiency.

3 (Top)Research Schools, Institutes, LTIs etc. with participation of groups ≥ 50%

All research groups at the departments of the three technological universities in The Netherlands with international scientific visibility in the area of fluid and solid mechanics participate in one of the following two well established inter-university Dutch Research (Graduate) Schools, namely:

- the J.M. Burgers Centre for Fluid Mechanics (abbreviated JMBC)
- the Engineering Mechanics School for Solid Mechanics (abbreviated EM).

Besides, there is substantial participation from the Dutch solid mechanics community in the Leading Technology Institute "Netherlands Institute for Metals Research" (abbreviated NIMR).

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5 Participating groups and central theme

The reoccurring theme of most of key areas mentioned at the end of section 2 is the coupling between very different length scales. It is the stumbling block of many of the unsolved problems. Therefore we define as central theme of the Centre of Excellence:

MULTISCALE PHENOMENA

The objective of the CoE is to achieve a better understanding of the macroscopic behavior of fluids and solids on the basis of the underlying structure and forces on smaller (e.g. microscopic) scales.

The ambition is to open up new horizons by solving a number of major problems both on the fundamental and the application side, thereby being recognized as a leading centre in this area on a world-wide scale and contributing in a major way to the Dutch industry and society.

An initial screening of top research groups, covering key activities required to implement a coherent and world-leading program on multiscale phenomena in fluids and solids, has led to the following list. We stress that other high quality, and sometimes just as essential, activities are available within the Centre of Competence. In fact, we aim at a dynamic structure of the CoE that can constantly respond efficiently to future opportunities and strategic choices.

Delft University of Technology

Professor	Chair	Year	Qual	Prod	Rel.	Viab.
Profs v.d. Akker / Kleijn / Mudde	Multiscale Physics	2004	4	4	4	4
Prof. de Borst	Engineering Mechanics	2002	5	5	5	5
Prof. van Keulen	Optimization and Computational Mechanics	N.A. [1]				
Prof. Wesseling	Numerical Analysis	2004	4	4	5	3
Profs Westerweel/Ooms	Fluid Mechanics	2000 [2]	5	4	4	5

Eindhoven University of Technology

Professor	Chair	Year	Qual	Prod	Rel.	Viab.
Prof. Geers	Mechanics of Materials	2000 [3]	5	5	5	5
Prof. van Campen	Dynamics	2000	5	4	4	5
Profs van Heijst / Clerx	Vortex Dynamics and Turbulence	1996	5	5	4	5
Prof. Mattheij	Analysis, Scientific Computing and Applications	2004	4	3	5	4
Prof. van Steenhoven	Energy Technology	2000	4	4	4	4

[1] No independent chair at last assessment of Mechanical Engineering in 2000

[2] Chair established in 2005. In 2000 Westerweel was staff member in group Nieuwstadt, whose 2000 ratings are given

[3] Chair established in 2000. Up to 2000 Geers was staff member in the Materials Technology group, whose 2000 ratings are given

University of Twente

Professor	Chair	Year	Qual	Prod	Rel.	Viab.
Prof. Huétink	Applied Mechanics	2000	4	3	4	4
Prof. Kuipers	Fundamentals of Chemical Reaction Engineering	2002	4	4	4	4
Profs Lohse / Prosperetti	Physics of Fluids	2004	4.5	4.5	4.5	4.5
Prof. van der Vegt / Geurts	Numerical Analysis & Computational Mechanics	N.A.				

For completeness we note that the grades are given by different, often local or regional evaluation panels, who have given different meanings to the same grade. A comparison of these grades is therefore difficult.

The selected chairs constitute a mixture of excellence (e.g. de Borst and Lohse have been awarded the Spinoza prize and de Borst, van Heijst and Lohse are members of the KNAW) and chairs that are expected to grow to excellence due to their embedding in the CoE.

6 Key themes addressed by CoE

- High-Tech Systems and Materials
- MinacNed (micro- and nano-technology)
- Health Science and Technology
- Environmental Technology

7 Sub-themes of KP-7 addressed by CoE

- Materials and production technologies
- Energy + environment
- Health

8 Three EU top groups in the area of the CoE theme

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9 Three EU top groups in the area of the CoE theme

Five new full 3TU chairs will be recruited by independent committees, consisting of outstanding and for the major part international scientists. For those chairs absolute top-researchers will be attracted. The chairs will be focused on the following topics:

- **Computational multiscale turbulence dynamics**

Turbulent flows are characterized by a large range of length and time scales, and therefore classified as a typical multiscale phenomenon. Turbulent kinetic energy is produced at the large scales and dissipated into heat at the small scales.
The new chair will focus on the numerical simulation of processes which occur at small scales in turbulent flows. Experimental validation of the findings will be crucial.

- **Reliability of structures and processes**

This new full chair will focus on reliability methods in computational mechanics. Reliability is a field of research that cross borders between the traditional disciplines of aerospace -, mechanical -, civil - and maritime engineering and is extremely relevant for many areas of engineering and production.

- **Computational physics of multi-scale transport phenomena**

The focal point of this new full chair is on transport processes in general microfluidic applications. This chair will have a societal impact by contributing to improved microfluidic devices for the sustainable production of hazardous chemicals and lab-on-a-chip applications, and to components of medical applications (production of pharmaceuticals, aspects of biosensor technology).

- **Small-scale structural dynamics**

Thin films and surfaces have an increasing influence on the behaviour of micro-systems as a natural result of the downscaling in miniaturization. A fully integrated numerical-experimental approach is required to tackle the problem. Typical topics that justify additional efforts to be concentrated in the new chair are: 1) microfluidic manipulation using microactuators forming ‘active walls’, 2) use of microfluidics to deform biological species (proteins, DNA, cells) to probe their mechanical properties and deformation characteristics and 3) micro-mixing.

- **Mechanics of interaction phenomena at multiple scales**

Cases where different physical phenomena simultaneously play a role, become increasingly important in many areas of engineering, e.g. in durability, joining technologies and biomaterials. The mechanics of interaction phenomena at multiple scales becomes even more relevant in the light of the ongoing miniaturization that necessitates to carry out the analyses at different levels of observation. The main thrust of this new chair will be to make fundamental contributions to novel computational techniques for capturing interaction phenomena.

The above completely new full chairs will play a key role in the focusing of the CoE (see also sections 10 and 11). To enable embedding of the new chairs in the TU departments after the five-year funding period, existing chairs inside and outside the Centre of Competence will be terminated. Commitments of the TU departments under concern have been obtained with respect to the embedding of the new chairs.

For each new full chair a more detailed description is given in section 6.2 of the report on this CoE, dated 15-12-2005.

Furthermore, one 3TU position for a part-time chair will be allocated to directly involve world-leading scientists in specific key areas of the CoE into our scientific programme.

9 New top-professors (and their professional areas) to be recruited

Five new full 3TU chairs will be recruited by independent committees, consisting of outstanding and for the major part international scientists. For those chairs absolute top-researchers will be attracted. The chairs will be focused on the following topics:

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Turbulent flows are characterized by a large range of length and time scales, and therefore classified as a typical multiscale phenomenon. Turbulent kinetic energy is produced at the large scales and dissipated into heat at the small scales.
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Furthermore, one 3TU position for a part-time chair will be allocated to directly involve world-leading scientists in specific key areas of the CoE into our scientific programme.

10 Focus of the CoE

The overall focus of the CoE is on multiscale phenomena in fluids and solids. The objective of the CoE is to achieve a better understanding of the macroscopic behavior of fluids and solids on the basis of the underlying structure and forces on smaller (e.g. microscopic) scales. Starting from the overall focus of the CoE, the following local focus is present within each TU:

Delft University of Technology
- Multi-scale turbulence dynamics and two-phase flow
- Optimization and reliability of engineering products and processes

Eindhoven University of Technology
- Multi-scale transport in fluids, ranging from sub-micron to global (geophysical) scales
- Integrated numerical-experimental approach to materials characterization for the analysis of multi-scale problems

University of Twente
- Multi-scale phenomena in multiphase flows
- Interaction phenomena at multiple scales

11 Societal drivers and technological dreams

Demand from society

Fluid and Solid mechanics is a field with many, but very diverse applications. So there is not only one application dream such as e.g. in fusion physics. There are many diverse and often very unexpected ones. Section 9 of the report on this CoE, dated 15-12-2005, surveys seven challenging examples for the application of the knowledge. Two of those examples, which will certainly be addressed by this CoE, are given below.

A new class of smart and self-renewing materials, relying on the careful design of microstructures with metastable phases
The key focus is to change various properties of materials during service, whereby an external field (kinematical, electrical, magnetic, thermal, etc.) is used to trigger phase and state changes.

Micro-fluidic devices for, e.g., the sustainable production of hazardous chemicals or pharmaceuticals, and lab-on-a-chip applications
Micro-fluidics is essential for a safe and sustainable chemical and pharmaceutical industry, in which distributed micro-reactors keep hazardous or toxic intermedia-tes at an absolute minimum inventory. Micro-reactors are required for minimizing the impact on the environment, for eliminating waste material, and for a sustain-able society. Application of micro-fluidic devices for lab-on-a-chip applications is also part of this technological dream.

12 Connected R&D perspectives

Demand from society

The most urgent and challenging problems in the fluid and solid mechanics of the 21st century are complex fluids, turbulence, micro- and nano-fluidics, the prediction of structural mechanical behavior from the material properties, nonlinear dynamics, tailoring/optimization of mechanical behavior, fluid-structure interaction, and solver efficiency. Some connected R&D perspectives are given below.

Complex fluids
The areas "granular flow" and "dispersed multiphase flow" are presently getting more and more interwoven. In liquids with bubbles the regime with a large gas-fraction and large bubbles is not understood at all, but particularly important from the point of view of applications. Another challenge lies in two-phase flows with phase-transitions (nucleation, condensation, evaporation).

Turbulence
Turbulence is the classical problem in fluid mechanics. The Clay foundation put Navier-Stokes turbulence into the list of the seven most challenging problems in mathematics and the Nobel committee has called it the last unsolved problem in classical physics. What makes turbulence and turbulent transport so complicated is the coupling of length- and time scales of very different orders of magnitude.

Micro- and nanofluidics
One of the fastest growing areas in fluid dynamics is that of systems with characteristic dimensions in the sub-micrometer to sub-millimeter scale. At these scales, fluid flow is dominated by interfacial phenomena. This requires a much better understanding of the interfacial boundary conditions, often down to phenomena at molecular scale. An important application is ink-jet printing. Here the challenge is to achieve even smaller droplets and even higher frequencies.

Prediction of structural mechanical behavior from the material properties
For many applications the prediction of structural mechanical behavior from material mechanics and the establishment of structure-property relations, including the ultimate failure of the material, would be very desirable. The ultimate aim is to quantitatively predict product properties.

Nonlinear dynamics
For many advanced mechanical products, processes and production systems (e.g. in precision technology, MEMS, NEMS and vehicle systems) it becomes of utmost importance to be able to predict their dynamic behavior with very high accuracy. Some of the many challenging topics in this area are impact systems, synchronization in nonlinear systems, nonlinear stochastic systems, control of nonlinear dynamic systems and reduced-order modeling.

Tailoring/optimization of mechanical behavior
One of the ultimate challenges in the competitive design of materials, (mechanical) products, processes and production systems is to use computer models based on their fluid and solid mechanics descriptions as a tool to tailor their mechanical behavior to preset requirements. Although from the practical point of view this area is still at its infancy, it will have tremendous future impact on competitive design.

Fluid-structure interaction
Fluid-structure interaction is becoming of increasing importance in various fields, both on small scales (e.g. in the medical context) or on large scales (e.g. oil platforms). To achieve any progress, a two-way coupling is essential, i.e., the back reaction of the flexible structure on the flow must be taken into consideration.

A more extensive elaboration of the R&D challenges can be found in section 4 of the report on this CoE, dated 15-12-2005.

13 3TU MSc program on Fluid & Solid Mechanics

MSc program

Over the past years a 3 TU MSc program on Fluid & Solid Mechanics has been developed as a joint effort of the JMBC and EM Graduate Schools.

In the first year of this MSc program four joint (3TU) courses are profiling the MSc program on Fluid and Solid Mechanics and provide a basic layer of theory and knowledge related to this MSc program. The titles of these courses are: Advanced fluid dynamics; Mechanics of materials; Nonlinear & multibody dynamics; Turbulence.
Five program-related courses are aimed at further developing the program-related knowledge in the specific direction chosen.
Finally, the student's knowledge is further broadened by selecting another three courses from a list of approved courses or, alternatively by preparing already to some extent in the first year for the graduation project to be carried out in the second year.

The second year of the MSc program is concentrated on research and/or design.
The external traineeship prepares on the implementation of research and it is therefore done individually. This traineeship is either carried out in one of the other participating groups or in industry, a technological institute or an international sister group.
The graduation project is spent on a topic of theoretical or applied nature. Here the student can demonstrate and further develop his/her independent engineering and academic skills.

The specialization per location is completely consistent with the R&D focus for the individual groups. Together with the existing CoE and CoCo chairs the new full CoE chairs will gradually constitute the “heart” of the MSc program

14 Existing large facilities (≥ 1 M euro) and locations within 3TU

Infrastructure

Delft University of Technology

- For the research in the area of mechanics of micro systems the available infrastructure of DIMES is used, which enables a.o. to manufacture prototypes. Experiments are partly carried out in the MEMS lab which is currently being built.

- The laboratory facilities of the Fluid Mechanics Group include (i) a 24-meter pipe flow facility (40 mm diam.) for the fundamental investigation of transitional and turbulent pipe flow of Newtonian and non-Newtonian fluids; (ii) a 0.60x0.60 m2 boundary-layer water tunnel with a 5 meter long test section for optical flow diagnostics (PIV/LIF/PTV); (iii) a pressure vessel for the investigation of jet flow at low and high pressures (up to 16 bar). Equipment includes:
  - a high-speed stereoscopic PIV system including a dual-cavity Nd:YLF laser;
  - 3 stereoscopic PIV systems including Nd:YAG lasers;
  - an inverted epifluorescent microscope for micro-PIV and micro-LIF;
  - a stereomicroscope for 3D microscopic blood flow measurement in test animals.

- Group Multi-Scale Physics:
  - a 2”-inclined flow line for the research on annular two-phase flow. The length of the set up is 12m and it can be positioned in directions varying from vertical to just past horizontal. The set up is equipped with PDA and two tomographic film thickness gauges (based on measuring of local resistance).
  - a laser diagnostic combustion laboratory
  - a virtual reality lab for flow visualization

Eindhoven University of Technology

- In 2004 the Multi-Scale lab has been established in the Mechanical Engineering Department under the umbrella of the chair on Mechanics of Materials (Geers). The investment in equipment amounts to 2.5 MEuro and includes AFM, SEM, ESEM-FEG, Lateral force apparatus, Nano-indenter XP with CSM, as well as thermo-mechanical loading stage.

- - Laser-lab with a variety of lasers and cameras for PIV, stereo PIV and 3D-PTV
  - Rotating table facilities
  - Windtunnels
  - (Horizontal) water channels (including towing tank)

University of Twente

- High-speed Imaging system “Brandaris 128” (128 digital frames with imaging rates up to 25MHz).

- Twente (vertical) water channel with active grid and instrumentation.

- High-pressure lab with instrumentation and technical support (permitting experiments up to 500 bar).

- Particle image velocimetry (PIV) system with the corresponding lasers

15 New equipment to be financed from CoE-budget

Infrastructure

Investments will be done in the following new and challenging techniques to foster the exchange between the 3TU:

Three-dimensional optical imaging
Eindhoven: focus on simultaneous 3D velocity and temperature measurements. New equipment for 3D particle tracking velocimetry, combined with laser induced fluorescence: 200 kEuro.

Twente: focus on 3D PIV for two-phase flow with bubbles and particles.
New 3D PIV equipment for dilute multi-phase flow: 350 kEuro.

Three-dimensional tomography
Delft: focus on flow geometries and multi-phase flows for which relatively high y – radiation is required for the tomography.
New equipment for tomography (strong radiation): 200 kEuro.

Twente: focus on application of y – radiation 3D tomography under high-pressures in the Twente high-pressure laboratory (HDL).
New equipment for tomography (high pressure): 250 kEuro.

More information on the new equipment is given in section 7 of the report on this CoE, dated 15-12-2005.

16 Actions

Added value 3 TU cooperation

It is to be noticed that the existence of the JMBC and EM Graduate Schools has enabled structuring of the field of Fluid and Solid Mechanics over the 3TU as a whole and local focusing “avant la lettre”. Hence, there is already a tradition of very good exchange between the groups in the JMBC Graduate School and between the groups in the EM Graduate School. This holds both for cooperation between the groups within each TU and for inter-university cooperation. Detailed information is given in the second part of section 6.1 of the report on this CoE, dated 15-12-2005.
The new full chairs in the CoE do fit within the existing arrangements and will result in further focusing of the research at the each of the participating TUs, as indicated in section 10. This focusing is accompanied by an increase in critical mass at the 3 TUs and results in an increase of synergy in the CoE.
The sharing of infrastructure, combined with the focus of infrastructure within each TU, indicated in section 15, will further foster the exchange between the 3 TUs. The focus of the different groups of the CoE, both with respect to their research and with respect to their specific contribution to the MSc program will have the same effect.
Finally, the establishment of the CoE will enable the launching of a number of new large-scale Science Foundation programmes as specified in section 8 of the report on this CoE, dated 15-12-2005.

17 Valorization plan

Valorization

Valorization is of utmost importance to solve the Dutch knowledge paradox. In particular, this CoE is very well positioned to create a better balance between the generation of knowledge and its application in industry, with the ultimate aim to transfer knowledge into profitable business. To strengthen the interface between this CoE and the industry several initiatives will be taken to make the valorization process more effective. One is to draft a technology roadmap together with the industry, thereby aiming to enhance insight in the industrial needs in order to identify relevant long-term scientific research topics. Another initiative is to organize workshops to make clear which focus points in the research programme will lead to real breakthroughs in industrial applications. In this valorization process we will also involve the well functioning Industrial Advisory Boards of the JMBC and EM Graduate Schools as well as STW and the 3TU innovation lab for start-ups.

18 Budget needed for items 9 and 15

Budget

Sections 9 and 15 imply the following budget for this CoE (numbers in kEuro):

Overall

• 5 new full 3TU chairs	5 x 1.0 M euro =	5.0	M euro
• 2.5 new 3TU UDs connected to new full chairs	2.5 x 0.6 M euro =	1.5	M euro
• 1 part-time 3TU chair		0.5	M euro
• Equipment		1.0	M euro
Total:		**8.0**	**M euro**

Budget **Specification**

• **5 new full 3TU chairs**		
- Computational multiscale turbulence dynamics	1.0	M euro
- Reliability of structures and processes	1.0	M euro
- Computational physics of multiscale transport phenomena	1.0	M euro
- Small-scale structural dynamics	1.0	M euro
- Mechanics of interaction phenomena at multiple scales	1.0	M euro
• **2.5 new 3TU UDs connected to new full 3TU chairs**		
- 0.5 UD connected to new full chair on Computational Multiscale turbulence dynamics and to existing full chair on Numerical Analysis	0.3	M euro
- 0.5 UD connected to new full chair on Small-scale structural dynamics	0.3	M euro
- UD connected to new full chair on Mechanics of interaction phenomena at multiple scales	0.6	M euro
- 0.5 UD connected to new full chair on Mechanics of interaction phenomena at multiple scales and to existing full chair on Numerical analysis and computational mechanics	0.3	M euro
• **Part-time 3TU chair**	0.5	M euro
- **New infrastructure**		
- New equipment for 3D high y – radiation X-ray tomography	0.2	M euro
- New equipment for 3D particle tracking velocimetry, combined with laser induced fluorescence	0.2	M euro
- New equipment for 3D dilute multiphase flow measurement	0.35	M euro
- New equipment for y – radiation X-ray 3D tomography under high pressures	0.25	M euro

19 Budget needed for items 17

Budget

To be set up for each individual case.