Publishable Summary for 16ENG06 ADVENT
Metrology for advanced energy-saving technology in next-generation electronics applications

Overview

The roll-out of 5th Generation (5G) telecommunications across Europe started in 2020. This coupled with the emergence of the Internet of Things (IoT) with its potentially 50 billion connected and continually operating electronic devices, will strongly increase the demand for energy leading to an associated need for more energy-efficient systems. This project has provided traceable measurements of power, losses and emerging electronic materials properties and the scientific knowledge required for the development of ultralow power devices. This is a significant contribution that will enable the European electronics industry to reliably develop more efficient power managements systems for next generation ultra-low power devices.

Need

The ongoing IoT and the future 5G radio access network will have a fundamental impact on the daily life of all European citizens. Sensors, the cornerstone of IoT, will be everywhere – in the car, the house, in industrial process monitoring etc. 5G communication systems will provide greater connectivity important in high speed Machine-to-Machine data exchanges with low time before response (latency). The high data-rate aspect of 5G at mmWave frequencies makes power consumption and thermal energy losses as heat very challenging to manage in wireless devices. The global greenhouse gases emissions in the Information and Communications Technology (ICT) sector has increased by half since 2013, rising from 2.5% to 3.7% of global emissions ("Lean ICT - Towards Digital Sobriety", The Shift Project, March 2019). Within this, 20 % of the footprint is attributed to personal mobile networks and mobile devices. Phones and tablets have produced the strongest percentage increase of greenhouse gas emissions in the ICT footprint.

Traceable and accurate data produced by innovative power sensors are needed to enable European mobile device manufacturers to improve their power management system efficiency and operating lifetime. This is particularly important for battery technologies used in smartphones and tablets. Multi-disciplinary metrology approaches proposed in this project will support the ICT sector's development of ultra-low power devices and therefore aids reduction of the European (and global) carbon footprint. The lower the power consumption of an electronic device, the longer it will continue functioning without recharging or changing the battery.

Improvement of the energy efficiency of devices and processes is therefore a key component for sustainable development of European products. Due to restrictions in current scaling strategies and dramatic thermal issues (particularly in wireless systems), semiconductor and electronics manufacturing roadmaps are aimed at the introduction of novel materials, more complete component characterisation and more efficient power management at the system level that will lead to the development of novel ultra-low power devices. To support industry in facing these challenging issues, traceable measurement techniques have been developed in this project to establish a robust metrology framework for in-situ, in-operando and multi-physics characterisation of advanced materials and components, and for reliable and accurate data for an efficient power management system.

Objectives

The overall objective was to achieve traceable and accurate measurements of the power consumed by ultra-low power and high frequency energy efficient electronic materials, devices and systems in order to support their development in both industrial and research sectors.

The specific objectives of the project are:

1. To develop nanometrology adapted to the in-situ and operando characterisation of advanced new materials proposed for the next generation of ultra-low power energy-efficient devices. These

measurements will include impedance measurements (capacitance, resistance and inductance), piezo-electric/piezoresistive stress (200 MPa) and strain (0.02 %) responses to the application of electric (up to 4 MV/cm) and magnetic (up to 2 T) fields, as well as temperature and pressure in the range encountered in electronic devices.

2. To develop frequency and time-domain techniques for the simultaneous measurement of dynamic thermal profiles, electro-magnetic field sensing, DC electrical power consumption and RF operating waveforms for a wide range of RF electronic components (operating in-situ, under realistic conditions). These techniques to be combined with a multi-physics approach, which will establish rigorous energy budgets, and diagnostic capabilities, for a wide range of electronic components (operating in-situ, under realistic conditions), required for next-generation communications. The uncertainty in the measurement of the power efficiency to be reduced to less than 1 %.
3. To develop embedded sensors and the associated calibration and measurement techniques to accurately measure power consumption of wireless systems (mobile phones, tablets and connected devices) and to improve the effectiveness of analogue and RF tests of components and systems. The power measurement techniques will be able to characterise and calibrate on-chip power sensors with an uncertainty of less than 10 µW.
4. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories), standards developing organisations (ISO) and end users (the semiconductor industry, and the telecommunications sector).

Progress beyond the state of the art

This project has involved three complementary elements (materials, components and systems) to support European industries in the development of optimised energy devices and systems required for 5G and IoT applications.

Materials

The characterisation of novel materials, such as ferroelectric, multiferroic, and piezoelectric-resistive materials, important in development of ultra-low power devices, requires a joint effort in improved impedance, material structure and compositional metrology. Before the start of the project, the impedance measurement and structural analysis at nanoscale of such materials was suffering from a lack of traceability, insufficient resolution and reliability. This project has developed a broad platform of measurements to extend the spatial resolution of material structure and composition to the nanometre scale, to quantify impedance of novel materials with an uncertainty of 10 %, and to extend measurement of stress and strain responses to electric field up to 4 MV/cm and magnetic fields up to 2 T.

RF components

RF electronic components are never single transistors therefore, it is critical to understand design limitations by measuring the electromagnetic fields, temperatures, and losses distribution as the device operates. As a result of this project, a European metrology solution for simultaneously measuring of the electromagnetic and thermal responses of RF and microwave components under realistic operating conditions and also for measuring switching losses accurately has been generated. This project has combined a range of contacting and non-contacting techniques to reduce the current uncertainty in evaluating the power efficiency of such electronic components from 2 to 1 %. A method has been developed to measure the switching losses with associated uncertainties down to 1 % for a large of DC current levels, has been developed and used on GaN transistors that provided the opportunity to realize an analysis of the loss components needed to develop low energy consumption switching devices.

Systems and devices

To optimise the power consumption and system performance of battery-supplied devices, it is necessary to monitor and adjust the transmitted RF power accurately and continuously. On-chip power levels measured in these devices can be as low as several microwatts. Even if many semiconductor chip suppliers are increasingly integrating power and thermal measurements into their devices, the traceability of on-chip power measurements does not exist in NMI facilities. This project has developed traceable high frequency power metrology for on-chip power measurements with traceability established to the national primary standards available at NMI.

Results

Nanometrology for characterisation of new materials

This objective was to develop the metrology required in Europe for the measurement of impedance at nanoscale and characterisation of advanced materials such as piezo and ferroelectric materials. Scanning Microwave Microscopy (SMM) instruments are used to measure impedance at nanoscale and require traceability to International System of Units (SI) through capacitance, resistance, and inductance standards. Different standards (capacitance values from attofarad to femtofarad, resistance values from milli-Ohm to kilo-Ohm, inductance values from picohenry to nanohenry) have been designed and manufactured by NMIs involved in the project and their characterization has been carried out. The uncertainties on capacitance measurements using capacitance standards fabricated are within the range of 10 % uncertainty as targeted at the beginning of the project. Furthermore, to investigate different aspects affecting the results, the SMM environment has been modified to perform experiments at different relative humidity levels (from 1 to 45 %). To our knowledge, this is the first time that the impact of humidity has been determined on SMM capacitance measurements. To improve the reliability of dielectric constants of promising ferroelectric and piezoelectric materials, an SMM measurement campaign was carried out using two different piezoelectric materials after deposition of gold pads on their top surfaces. A strong variation in dielectric constant was observed between NMIs indicating that measurement procedures for piezoelectric measurements in the presence of humidity need further investigation and improvement. Mesoscale and analytical in-situ X-ray characterisation studies, and complementary nano-measurement techniques have been applied in this project on piezoelectric samples under different conditions. These latter were: electric fields in the frequency range a few MHz to 1MHz, stress/strain from a few MP to 60 MP and over 0.1 MV/cm, magnetic fields to 3 Tesla and temperatures up to 450 K. In this project for the first time, the application of an electric field (200 kV/cm), using Transmission Electron Microscopy (TEM), has demonstrated the feasibility of strain measurements on phase changes. Infrared Scanning Near-Field Optical Microscopy (IR-SNOM) had been more recently applied to measure strain. Modelling was used with both techniques to confirm/validate results: in TEM to evaluate the effects of strain relaxation in the thin electron-transparent lamellae, and in IR-SNOM to interpret the spectral shifts in terms of strain. The Focused Ion Beam Milling (FIB) technique used in specimen preparation has been considerably improved which allows the move to in-situ biasing experiments for IR-SNOM and TEM techniques under real in-service conditions for the first time. In order to correlate the chemical composition and electrical properties of piezoelectric materials, a set of lamellas were successfully prepared by FIB and measured using SMM. The phase map thickness measurements obtained were in good agreement with the TEM data obtained. This objective has been fully achieved.

Multiphysics characterisation of RF components

This 2nd objective was to develop and combine time- and frequency- domain, electromagnetic field and thermal mapping measurement techniques to establish rigorous energy budgets, and diagnostic capabilities, for a wide range of electronic components (operating in situ, under realistic conditions), required for next-generation communications. The experimental setup for Scanning Thermal Microscopy (SThM) measurements for the novel electronic characterization of available probes and IR (Infrared) measurements has been significantly improved. These improvements have been applied to measure large area temperature distribution of real devices (HEMT Cree device transistors) with low (100 nm) and high (20 nm) resolutions in active or passive modes. Moreover, it was found that for each of the methods, there are disadvantages that can be suppressed by using both methods combined. An emissivity map is better when determined using temperature measurement with SThM instead of the infrared method. On the other hand, once the emissivity is known, the infrared method is better than SThM at measurement of high temperatures. The accuracy and precision of temperature measurements cannot be easily specified as it depends very much on the emissivity of the surface and the duration of the measurement. Several different situations were analysed with a worst-case result of $T = (112 \pm 23)$ °C and a best-case result of $T = (167.50 \pm 0.14)$ °C. SMM measurements have been applied on AlGaN samples that constitute the basis of field effect transistors: qualitative results were not obtained because of the lack of contrast between the different materials layers in images captured by SMM. In order to support the Scanning Probe Microscopy (SPM) techniques used for measuring local properties at nanoscale (dopant density, permittivity), novel numerical tools have been implemented to enable performance of pixel-by-pixel virtual SPM image generation for different SPM modes. The goal of pixel-by-pixel simulations was to create a numerical counterpart to the experimental measurements, using the known probe-sample interaction and the modelling of a virtual image, based on a structural model of the sample. For the multiphysics approach, Load-Pull and Electro-optic Electric Field Sensing techniques as well as Load-Pull and Thermoreflectance Temperature techniques have been integrated into a single experimental setup and this has been applied to real devices enabling power efficiency to be related to physical data for the first time. To emphasize this new capability, a GaN transistor has been measured and “max Pout” and “max efficiency” conditions have been demonstrated during the transistor’s operation. Different thermal rise times between the fingers of the transistor studied were also observed under “max Pout” conditions. To enable characterization of the device to be made under realistic microwave drive conditions, thermal and electric field measurements were made with the load tuner set to the load impedances corresponding to maximum efficiency (“max efficiency”) and to maximum output power (max Pout) as determined by the load-pull measurements. There is a trade-off between the maximum output power and the maximum efficiency obtainable from the device. In addition, higher output power results in a higher power dissipation, which means that increased heating will occur within the transistor. This link, established between power efficiency and physical data (e.g. temperature), is of great importance for the design of electronic devices. Regarding the time domain method developed in this project to measure the switching losses, different approaches have been investigated to reduce measurement errors and main error sources were analysed. The following methodology focuses on the characterization of the losses in high-speed switching devices for power electronics applications with rise time in the nanosecond range, thus having significant spectral components up to, approximately, 1 GHz. This is the case of GaN FET power transistors employed in hard-switching power converters. A loss component analysis has been performed on this device for different levels of DC current. The analysis provides the distribution of the different contributions to the total losses that emerge from distinctive phenomena that occur during the switching process. It allows an understanding of which aspects should be controlled, from an electronic design point of view, for optimizing the efficiency of the circuit. From the analysis it’s evident that dynamic losses represent between 80 - 60 % of the total losses in the power converter. Therefore, for improving the efficiency in power converters the most important loss component to consider are the switching loses, that is, the faster the rise and fall times are, the higher the efficiency in the power conversion. For output currents that drive the power converter circuit to the optimal operating conditions, the relative uncertainty approaches the ± 1% targeted at the beginning of the project. This objective has been fully achieved.

Power consumption measurement of wireless systems and devices

This 3rd objective aims to provide to industry low cost and traceable power sensors and fast scanning measurement data to improve on-chip power traceability. Two types of power sensors have been fabricated. Each design has its own advantages and the most promising one is the zero bias detectors with temperature compensation. This latter can be an ideal solution when the power consumption (battery life) is crucial, as is the case of 5G applications; and provides robust performance against the variation of ambient temperature as is the case of IoT sensors. The traceability of this power sensor is based on chip direct comparison system and on chip power standard. The on-chip power standard has been fabricated on GaAs substrate. The standard and the power sensors have been completely characterized in terms of matching, linearity, sensitivity and scattering-parameters. The performance of the standard and power standards obtained with respect to the requirements up to the targeted frequency of 42 GHz have been validated. The power sensor has been calibrated on chip by comparison with the power standard. The power sensor and power standard have been compared in terms of power reading. The traceability of on chip power sensors to the System International of Units (SI) has been demonstrated through this comparison. Regarding the fast scanning approach, a third method has been developed to improve and overcome limitations of the previous ones. The goal of this method is to monitor the power consumption of Printed Circuit Boards (PCBs) using near field measurements above circuits under tests. This last method operates by extracting the magnitudes of the reflection (S11) and transmission (S21) coefficients from the shape of the near magnetic field curves along a transmission line or between two locations of a circuit. Using these data is possible to obtain an estimation of power losses. In parallel, a low frequency standard (active current shunt) has been fabricated in order to link on-chip power measurements to low frequency standards. This current shunt has been tested and the results demonstrate its ability to measure very small levels of currents (50 nA to 200 µA) up to the megahertz range. The measurement results of the current shunt and high frequency approach based on VNA have been compared on microstrip transmission lines. The uncertainty level of 10 µW initially targeted on the absolute power measurement was not demonstrated but instead the uncertainty of the power consumption ratio ranging from 0.0018 to 0.032. Target achievement of 10 µW will depend on the power injected in the device under test. The deliverable has been partially achieved because the uncertainty on the power ratio consumption has been estimated instead of the uncertainty of absolute power consumption. Additional absolute power measurements would had been necessary.

Impact

To date, 39 presentations and 6 posters have been made to conferences at various European locations, 15 papers have been accepted for publication during the lifetime of the project (these papers are all open-access publications). The project partners have submitted 3 articles to trade journals during the lifetime of this project. Two workshops and one training session took place in February 2019, September 2019 and November 2019.

A workshop “X-ray and Neutron Scattering and Spectroscopies in Ferroelectric and Multiferroic Research Workshop V” was held at IOM3 (The Institute of Materials, Minerals and Mining) in London on 4-5 February 2019. This workshop promoted project developments to 55 European, Asian and American experts from the multiferroics, magneto-electrics and ferroelectrics communities and neutron, synchrotron and spectroscopy facility end-users. Workshop participants were impressed by the high level of technical knowledge shown by the ADVENT presentations and were particularly interested in the results obtained using diffraction and Transmission Electron Microscopy methods.

A second workshop, “Microwave measurements at systems, components and materials levels: a global approach to improve energy efficiency of the next generation of electronic devices” was held in Paris during the European Microwave conference (September 2019).

The project’s training course “Uncertainty in measurements for next-generation high frequency applications” was held at NPL (Teddington, UK) in November 2019 for early career stage attendees. It provided an opportunity for attendees to learn uncertainty methods, to have discussions with key high frequency metrology experts and to discover the current state of the art in S-parameters and permittivity measurements.

Impact on industrial and other user communities

A project advisory group (PAG) with members drawn from the semiconductor, electronic, instrumentation, research sectors and academia provided feedback on the projects strategy and results throughout the project via both physical and video meetings.

A meeting was organised on 9th April 2018 at LNE Trappes (France) with two key representatives from Alliance Electronique. This organisation is the major French professional union for industry and manufacturers in the electronics sector. During this meeting, a discussion was carried out to organise the dissemination of results to manufacturers and industrial members of Acsiel Alliance Electronique.

Stakeholders and collaborators of the project have already been able to take advantage of project outputs through early access to open access publications including measurement results explaining the limitations and potential functionalities of materials they are using and or which are under development.

Calibration kits to improve the reliability of impedance measurements at the nanoscale, as performed by end-users such as the academic community and the semiconductor industry will also be available shortly. Fabrication of calibration kits have been detailed and disseminated to large community of end-users through open access publication published during the project (conferences and paper accepted in peer-reviewed journals).

Impact on the metrology and scientific communities

The current development of capacitance and inductance standards enables traceability of impedance, permittivity and loss measurements to be established at the nanoscale. These advances will extend the measurement capabilities of the leading European NMI project partners in terms of the characterization of advanced materials such as ferro-electric, multi-ferroic, and piezoelectric-resistive materials important to the electronics industry. The project’s multi-physics approach has already improved measurement capabilities and expertise of project partners involved in microwave component characterization and for the first time in Europe measurement devices operating under non 50 Ω conditions have been robustly investigated.

Research in the project on on-chip power measurements has created new power measurement detectors with capabilities based on the latest BICMOS 55 nm technology and the most advanced instrumentation is a world first. Using the latest fabrication processes based on project developed technologies has improved the experience of early users in both the industrial and academic sectors. These detectors have potential for exploitation by electronic component manufacturers engaged in 5G-product development because they are based on the latest ST Microelectronic technology. Detectors have been developed, manufactured and characterised: their performances (sensitivity, matching, and linearity) are excellent at 42 GHz. One of them is based on zero power consumption that is of great importance for energy saving devices.

Impact on relevant standards

Project progress and engagement was disseminated to IEC (TC 47, 49 and 113), ISO (TC206), IEEE (P1859/D6), VAMAS (TWA24) and EURAMET TC-EM SC-RF&MW/EMC, and SC-LF committee meetings. These reports describe the dissemination of good practice guides and the organisation of meetings dedicated to standardisation activities relating to semiconductor devices, piezoelectric and dielectric devices and characterisation of materials at the nanoscale. The consortium has also interacted with CEN/CENELEC/ETSI "Sector Forum Smart and Sustainable Cities and Communities" with a view to presenting the projects results to the appropriate CEN/CENELEC standards committee.

Longer-term economic, social and environmental impacts

The new traceability measurement capabilities for impedance developed in this project will aid the industrial competitiveness of European nanoscale measurement instrument manufacturers and supports the development of technical innovations in the ICT sector. Dissemination of improved characterisation methods for piezo and ferroelectric material under realistic in-service conditions will generate a European skills base that can support European electronics industry innovation and competitiveness. The new European power efficiency evaluation capabilities based on the multi-physics approach developed in this project, now enable reliable evaluation of electronic component heating effects – an important step in future ICT product innovations.

List of publications

1. Bernd Kästner, Franko Schmähling, Andrea Hornemann, Georg Ulrich, Arne Hoehl, Mattias Kruskopf, Klaus Pierz, Markus B. Raschke, Gerd Wübbeler, and Clemens Elster, "Compressed sensing FTIR nano-spectroscopy and nano-imaging", Optic Express, April 2018, https://doi.org/10.1364/OE.26.018115.

2. Bernd Kästner, C. Magnus Johnson, Peter Hermann, Mattias Kruskopf, Klaus Pierz, Arne Hoehl, Andrea Hornemann, Georg Ulrich, Jakob Fehmel, Piotr Patoka, Eckart Rühl, and Gerhard Ulm, "Infrared Nanospectroscopy of Phospholipid and Surfactin Monolayer", ACS Omega, April 2018, https://pubs.acs.org/doi/10.1021/acsomega.7b01931

3. Joao Carlos Azevedo Goncalves , Issa Alaji , Daniel Gloria , Vincent Gidel , Frederic Gianesello , Sylvie Lepilliet , Guillaume Ducournau, François Danneville, Christophe Gaquière, "On Wafer Millimetre Wave Power Detection Using a PN Junction Diode in BiCMOS 55 nm for In-Situ Large Signal Characterization", 48th European Microwave Conference (EuMC), Madrid Spain, September 2018, https://zenodo.org/record/4294934#.X8M6y81Kg2x

4. Joao Carlos Azevedo Goncalves; Issa Alaji; Daniel Gloria; Sylvie Lepilliet; François Danneville; Christoohe Gaouierc; Gu "Investigating the potential of SiGe Diode in BiCMOS 55nm for power detection and datacom applications at 300 GHz", 2018 43rd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Nagoya Japan, September 2018, https://zenodo.org/record/4295560#.X8M60s1Kg2x.

5. T. Le Quang, D. Vasyukov, J. Hoffmann, A. Buchter, M. Zeier, "Fabrication and Measurements of Inductive Devices for Scanning Microwave Microscopy", IEEE-Nano, July 2019, https://zenodo.org/record/4275929

6. Kendig, D., Votsi, H., Urbonas, J., Matei, C., "Dynamic Temperature Measurements of a GaN DC/DC Boost Converter at MHz Frequencies", IEEE Transactions on Power Electronics, January 2020, DOI: 10.1109/TPEL.2020.2964996, OA link:http://epubs.surrey.ac.uk/853825/

7. M. Staruch, H. ElBidweihy, M. G. Cain, P. Thompson, C. A. Lucas, and P. Finkel, "Magnetic and multiferroic properties of dilute Fe-doped BaTiO3 crystals", March 2020, http://dx.doi.org/10.1063/5.0002863

8. Jose A Moran-Meza, Alexandra Delvallée, Djamel Allal, François Piquemal, "A substitution method for nanoscale capacitance calibration using scanning microwave microscopy", April 2020, https://doi.org/10.1088/1361-6501/ab82c1

9. M. Wansleben, J. Vinson, A. Wählisch, K. Bzheumikhova, P. Hönicke, B. Beckhoff, and Y. Kayser, “Speciation of iron sulphide compounds by means of X-ray Emission Spectroscopy using a compact full-cylinder von Hamos spectrometer”, May 2020 , https://arxiv.org/abs/2005.09509

10. E. A. Patterson, M. Staruch, B. R. Matis, S. Young, S. E. Lofland, L. Antonelli, F. Blackmon, D. Damjanovic, M. G. Cain, P. B. J. Thompson, C. A. Lucas, and P. Fink, “Dynamic piezoelectric response of relaxor single crystal under electrically driven inter-ferroelectric phase transformations”, June 2020, https://livrepository.liverpool.ac.uk/3091334/

11. Markys Cain, Margo Staruch, Paul Thompson, Christopher Lucas, Didier Wermeille, Yves Kayser, Burkhard Beckhoff, Sam Loafland, Peter Finkel, “In situ electric-field study of surface effects in domain engineered Pb(In1/2Nb1/2)O3-Pb(Mg1/3Nb2/3)O3-PbTiO3 relaxor crystals by grazing incidence diffraction”, September 2020, https://doi.org/10.3390/cryst10090728

12. Marco A. Azpúrua, Marc Pous, Ferran Silva, “Uncertainty Analysis in the Measurement of Switching Losses in GaN FETs Power Converters”, 2020 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), 2020. https://upcommons.upc.edu/handle/2117/328678

13. J. Barnett, M-A. Rose, G. Ulrich, M. Lewin, B. Kästner, A. Hoehl, R. Dittmann, F. Gunkel, T. Taubner, “Phonon-Enhanced Near-Field Spectroscopy to Extract the Local Electronic Properties of Buried 2D Electron Systems in Oxide Heterostructures”, September 2020, https://doi.org/10.1002/adfm.202004767

14. T. Janda, J. Godinho, T. Ostatnicky, E. Pfitzner, G. Ulrich, A. Hoehl, S. Reimers, Z. Šobáň, T. Metzger, H. Reichlová, V. Novák, R. P. Campion, J. Heberle, P. Wadley, K. W. Edmonds, O. J. Amin, J. S. Chauhan, S. S. Dhesi, F. Maccherozzi, R. M. Otxoa, P. E. Roy, K. Olejník, P. Němec, T. Jungwirth, B. Kaestner, and J. Wunderlich, “Magneto-Seebeck microscopy of domain switching in collinear antiferromagnet CuMnAs”, September 2020, https://arxiv.org/abs/2004.05460.

15. Issa Alaji Walid Aouimeur Haitham Ghanem Etienne Okada Sylvie Lépilliet Daniel Gloria Guillaume Ducournau Christophe Gaquière, Microwave and Optical Technology Letters, “Design of tunable power detector towards 5G applications”, October 2020, https://zenodo.org/record/4300488#.X89k0252uUm

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1st September 2017, 36 months</td></tr>
<tr><td colspan="3">Coordinator: François Ziadé, Dr., LNE   Tel: +33 1 30 69 21 71   E-mail: francois.ziade@lne.fr
Project website address: http://projects.lne.eu/jrp-advent/</td></tr>
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1 LNE, France
2 BAM, Germany
3 CMI, Czech Republic
4 JV, Norway
5 NPL, United Kingdom
6 PTB, Germany</td><td>External Funded Partners:
7 CNRS, France
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