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At its meeting on April 7, 2016, the French-German Council of Ministers emphasised again the importance of the interoperability of the French and German armed forces as well as that of the French-German defence cooperation. These are fostered by joint military requirements and are certainly supported by joint research and technology activities. ISL has committed itself to this goal for more than 57 years.

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At our binational research institute, French and German scientists and engineers bring disruptive technologies to life, prompting a growing academic renown, while serving the needs of ISL’s defence and security stakeholders. This academic recognition provides the benchmark ensuring that ISL’s scientific output is at the forefront of innovation. Our proximity to the end-users of our research ensures that it remains focussed on their needs.

ISL’s four main research topics, i.e. materials research including explosives, flight techniques for projectiles, new electric effectors such as eye-safe lasers and electric guns, and protection technologies, rest on a broad range of competences. The breadth of the research portfolio and the depth of the research investigations are often in opposition. But ISL’s unique mix proves to be surprisingly efficient. Its scientific portfolio, its facilities ranging from complex simulations to free-field testing and its comprehensive approach nurture a wealth of tangible solutions. ISL acts as an R&T one-stop shop, unique in Europe, to the benefit of the frontline soldiers and first responders.

ISL does not work in isolation. On the contrary. We leverage the skills of many external partners, with a view to consolidating their added value on selected defence and security issues. With 41 PhD students at the end of 2016, ISL ensures a close cooperation with just as many academic research teams, as we purposefully choose doctoral supervisors outside ISL. We further collaborate with other laboratories within the framework of common projects funded by various research funding organisations. We define the milestones of our scientific roadmaps, so that the strategic decisions of the French and German defence and security procurement organisations with respect to technology projects may be carried out on sound bases. We exchange continuously with the defence and security industry, and other national research institutes fulfilling defence tasks in complementary domains, so as to bring unique contributions where they are most needed within ISL’s portfolio of competences.

Here is a selection of results achieved in 2015 and 2016:

- ISL’s powder metallurgy, including powder production and powder sintering through the SPS process, produced aluminium samples with considerably improved hardness and strength characteristics;
- The patented manufacturing process of very insensitive RDX (V- RDX) – a specific grade of a common explosive that provides a much lower shock sensitivity – was further optimised. The production efficiency could be increased from 35% to 60%. A licence agreement was signed at the end of 2015, and ISL assists the scaling-up by the licensee through a support contract;
- Promising substitutes for propellant stabilisers were developed, in compliance with the REACH regulations, preventing the formation of carcinogenic by-products. Furthermore, research was conducted on an energetic mixture of nano-explosives and nanothermites, making it possible to initiate a detonation in a secondary explosive without (highly unstable) high explosives;
- The miniaturisation of g-hardened, low-cost sensor and effector suites, which are needed for future guided projectiles, experienced a further leap forward, with a reduction factor of 2 to 3 for electronic board technology embedding on-board transmitters, sensors and multiplexers, allowing for example long-range bidirectional communication with the projectile with 16-mm-diameter modules;
- An innovative concept for long-range projectiles was developed and is patent-pending: this may lead to doubling the existing ranges;
- In the laser field, ISL made a significant contribution to the protection against incoming threats with new beam-shaping optics developed at ISL and allowing a perfect overlap of emission bandwidths I and II. They were successfully field tested at the Technical Centre for Protective and Special Technologies (WTD 52) in Oberjettenberg (Germany);
- The latest developments with respect to the PEGASUS railgun allow the acceleration of representative projectiles, at initial velocities of more than 2300 m/s with an efficiency of up to 37%, a world record according to the open literature. In parallel, compatibility of explosive-loaded projectiles and on-board electronics has been successfully tested with the high electromagnetic fields developed by the railgun;
- ISL’s unique acoustic detection and active imaging technologies were combined and successfully demonstrated during field tests in Germany for the purpose of detection, reconnaissance and localisation of Unmanned Aerial Vehicles (UAVs). The unique range-gating capability of active imaging was successfully used to silhouette flying objects against very structured backgrounds, such as foliage or urban landscape;
- A time-resolved acoustic localisation model, based on the time of arrival in combination with a 3D propagation model, was specially developed to localise threats in urban areas. First validation tests confirmed the prospects in this very promising technology.

These scientific achievements and others have earned ISL further recognition from the international scientific community, confirmed by the numerous prizes and awards granted to various ISL research teams. A selection of these are recorded page 16–17.

The highly qualified scientific work provided by ISL’s unique scientific portfolio requires up-to-date and sometimes unique scientific platforms. In addition to a great number of small and medium acquisitions, ISL – in full accordance with its Steering Board – completed in 2015-2016 three major investment projects: a clean room, a trisonic wind tunnel and a new pyrotechnical complex on the proving ground.

In the following chapters, this annual report 2015/2016 gives you a broad survey of the research activities carried out at ISL, and a few selected snapshots. We wish you a pleasant reading!
FACTS AND FIGURES

2015

- 98 scientists
- 34 PhD students
- 92 engineers
- 50 technicians
- 63 workers
- 64 administration and support
- 2 apprentices

70% salaries
16% operating costs
14% investment

Budget*: 49.781 M€
(*VAT included)

2016

- 98 scientists
- 41 PhD students
- 87 engineers
- 53 technicians
- 61 workers
- 63 administration and support
- 5 apprentices

71% salaries
16% operating costs
13% investment

Budget*: 49.213 M€
(*VAT included)

- 122 documents written within the framework of contracts or agreements
- 164 publications (conferences, scientific journals, posters)
- 53 technical reports and papers

- 24% energetic and advanced protective materials
- 23% flight techniques for projectiles
- 21% laser and electromagnetic technologies
- 32% protection technologies, security, situational awareness

- 159 documents written within the framework of contracts or agreements
- 160 publications (conferences, scientific journals, posters)
- 47 technical reports and papers

- 26% energetic and advanced protective materials
- 22% flight techniques for projectiles
- 18% laser and electromagnetic technologies
- 34% protection technologies, security, situational awareness

1 List of selected ISL publications on our Website 2 List of patents and licences on our Website
Management team

From left to right:

Martin WINTER
Corporate Affairs

Magdalena KAUFMANN-SPACHTHOLZ
Communication

Pascale LEHMANN
Acting Head of Scientific Sector

Christian de VILLEMAGNE
French Director

Jean-Pierre MOEGLIN
Business Development Office

Marc EICHHORN
Laser and Electromagnetic Technologies

Bernd Michael FISCHER
Protection Technologies, Security, Situational Awareness

Christophe TAMISIER
Energetic and Advanced Protective Materials

Thomas CZIRWITZKY
German Director

Sandra LICHTENAUER
Quality, Security, Environment

Dominique CHARGELEUGUE
Flight Techniques for Projectiles
BUSINESS DEVELOPMENT & EVENTS

ISL has evolved over the years from an internal organisation of the Ministries of Defence, focussed inwards, to a full-blown research institution, fully comfortable within the academic world and also promoting applications of its technologies downstream.

How to access ISL technology?

ISL’s research output resulting from the ISL research programme benefiting both MoDs and thus funded by MoDs’ subsidies belongs to ISL. However, both MoDs receive all corresponding research reports (irrespective of the distinction between so-called “basic research” and “government contracts”) and enjoy a right of use for defence-specific purposes.

When a customer – be it a company or a government organisation - wants a specific research output that he only can use, whether it pertains to a customer-specific issue (in which case the research is de facto not benefiting both MoDs) or the customer wants exclusive rights, a so-called “third-party contract” must be placed. In this case, the property of the foreground information created by the third-party contract is defined within the contract: it may belong to the customer, or to ISL with a right of use for the customer.

In any case, ISL remains the owner of the background information, which may be licensed. ISL’s policy is to deliver non-exclusive licenses, so that in particular French companies may not bar German companies from an ISL technology and conversely.

Contracting with ISL

ISL’s Business Development Office acts as honest broker between ISL scientists and customers. Thanks to the unparalleled diversity of its research domains, ISL is capable of meeting a large variety of specific needs from customers, partners or project leaders, especially in the defence and security community, but also in important sectors of the civilian economy, such as the automotive and aerospace industries, the energy supply and storage field, or the biomedical engineering industry. Some third-party contracts are one-shot ventures, fulfilling a one-time need. ISL is, however, open to long-term partnerships, which may come with additional benefits for the customer, such as sharing and discussing technological roadmaps.

Offering new, added-value to the customers

For defence customers, two of the unique added values of ISL, beyond the topical excellence of its research portfolio, are its close connections with the operational forces in order to gain a better understanding of the needs of the end-users and the capability to extend its scientific output by leveraging collaborations with the academic world.

2015 and 2016 were years of intense exchanges with the academic world and the operational forces. Armament and defence topics cannot be easily treated in universities and civilian research institutes, especially in Germany, even when they are funded by the MoD. Thus, ISL signed a cooperation agreement with the Helmut Schmidt University of the Bundeswehr in Hamburg in March 2016 and reinforced its links with the University of the Bundeswehr in Munich. This ideal combination allows PhD students to be exchanged and research to be conducted in a dedicated environment with respect to defence and security themes.

The strength of ISL lies in its multidisciplinarity and interdisciplinarity, its reactivity and the fact that studies are conducted in one single place, from theoretical studies to simulations and real-life experiments, and mixing all scientific disciplines.

With so many advantages, no wonder that ISL’s third party business has increased significantly, especially over the past few years, so that it contributes already a sizable part of ISL’s budget. If you feel the need for new ideas and technological solutions in your current business situation, ISL will be your partner.

Fairs and Exhibitions

SOFINS | Bordeaux | April 14–16, 2015

ISL exhibited its high-end technologies at the SOFINS Special Forces Fair in Bordeaux. There were presented: Bio-inspired and autonomous Unattended Ground Sensor B-Saved, Gun-Launched Aerial Vehicle (GLMAV), Advanced protection materials, 3D audio display and portable eye-safe imaging goggle.

13th Summer University of Defence | Strasbourg | September 14–15, 2015

This meeting takes place in a different French region each year. In 2015 Strasbourg was the conference place chosen under the theme: “Reconnaissance and French-German dialogue”. ISL exhibited its know-how on two different locations: one at the CFIAR (Centre de Formation InterArmées au Renseignement) together with all the supply and logistics military services, and the other at the Congress Centre of Strasbourg.
ISL’s presence at the international armament fair EUROSA TORY was intensified in 2016. An enlarged exhibition booth was the meeting point for prominent visitors: the German Ambassador Nikolaus Meyer Landrut (2nd left) accompanied by General Zimmer (AIN) and the German Defence Attaché General Poth visited the ISL stand.

A second focal point at the fair was the DGA exhibition. The DGA had invited ISL to join other research centres and present recent innovative results. Thus the model of the new Spray Flash Evaporation process developed by ISL (see page 36) was shown in public for the first time. This patented process for the cocry stallisation of nanomaterials has been developed in collaboration with the French National Research Centre CNRS and the University of Strasbourg.

In 2016 ISL presented its new project BANG, a novel hearing protection device with integrated talk-through filter, developed within the framework of a DGA PEA in collaboration with COTRAL. Another interactive presentation displayed “Look around the corner”, a basic research project on computational imaging (see page 35).

At the DWT-Conference on “Trends in Defence and Security technologies – Research and Technology in Germany”, ISL presented the multiple aspects of its research in defence and security matters.

The ISL Budding Science Colloquium is a yearly conference organised by ISL to offer its 40 or so PhD students the best training conditions for presenting their work. ISL grants an award to the best oral presentation and the best poster. The prize for the best oral presentation was awarded to Jonathan Klein, for his presentation “Using 2D intensity images for tracking objects outside the line of sight”. The best poster was presented by Aro Ramamonjy for his “Drone detection, localisation and tracking using a network of compact differential microphone arrays”.

The French Defence Procurement agency (DGA) and the German “Bundesamt für Ausrüstung, Informatiktechnik und Nutzung der Bundeswehr” (BAAINBw) invited international experts in acoustics at ISL to participate in their joint workshop on “Battlefield Acoustics”. This biannual meeting gathers more than 100 experts to discuss about topics such as the acoustic environment on the battlefield, hearing protection, audio communication and situational awareness.
Business development & Events

NEW INFRASTRUCTURES

In 2015 and 2016 ISL significantly invested in its scientific equipment and infrastructure.

Meeting of the directors of the German Armament Research Institutes | ISL, Saint-Louis | October 05–06, 2016

Every year the German Ministry of Defence invites all the directors of the research institutes and testing centres to a meeting in order to harmonise strategy and programme planning. In October 2016 this high-level group met at ISL to visit the institute and discover the performance of the “Pegasus” electric railgun.

5th Workshop on Active Imaging | ISL, Saint-Louis | November 18–19, 2015

More than 100 scientists, operational staff, state representatives and industrial experts from different countries shared current information about operational needs, modelling, simulation and data processing and novel components in the field of active imaging systems. There was special focus on novel advanced imaging concepts such as compressed sensing, non-line-of-sight imaging and imaging with multisected photons or unusual wavelengths.


The “12th Laser Ceramics Symposium” (LCS), hosted by ISL and the City of Saint-Louis, took place from November 28 to December 2 in the new “FORUM” conference centre in Saint-Louis. The conference addressed research in transparent ceramics for laser applications and gathered experts and scientists in laser physics and materials science.

Inauguration of the new trisonic wind tunnel | ISL, Saint-Louis | June 25, 2015

The new wind tunnel is an exceptional scientific facility due to its technical characteristics. The wind velocity can be varied from Mach 0.5 (which corresponds to the speed of a train) to Mach 4.5, i.e. over 5,500 km/h. Thanks to the three operating modes (subsonic, transonic, and supersonic), projectiles can be tested under varying conditions in the test section of 30 cm x 40 cm during blow-down tests lasting for up to 60 s. The new facility is therefore particularly suitable for testing small-scale models of missiles and artillery shells, an essential step in defining the aerodynamic architecture of guided projectiles. The novel wind tunnel allows tests to be carried out at much lower costs than other existing facilities. Industrial partners and other research institutes have already expressed their interest in using this wind tunnel for their tests.

Inauguration of the E3 pyrotechnical complex at the ISL proving ground | ISL, Saint-Louis | June 22, 2016

French and German representatives of the Defence ministries and local authorities discovered the brand-new E3 pyrotechnical complex at the ISL proving ground. After 3 years of construction, this pyrotechnical plant equipped with advanced video-assisted manufacturing systems as well as with specific laboratories and storage depots for energetic materials now offers a secure environment for the handling of larger amounts of propellants and explosives, increasing ISL’s efficiency and reactivity, and enabling “real life” tests.
Awards

2015 Awards

Guy Ourisson Prize
Dr. Vincent Pichot, an ISL scientist from the NS3E* (Nanomaterials for Systems under Extreme Solicitations), was awarded on January 23, 2015 the “Guy Ourisson Prize 2014” granted by the “University of Strasbourg Foundation-Cercle Gutenberg.”

Lazare Carnot Prize
Dr. Denis Spitzer, Director of the NS3E*, was awarded the “Lazare Carnot Prize” from the French Academy of Sciences for his fundamental research in the field of energetic nanomaterials and his work on the continuous nanocrystallisation of organic matters.

NATO SET Panel Excellence Award
Two members of the French-German Research Institute of Saint-Louis (ISL), Dr. Christelle Kieleck, a scientist from the DPA (Directed Photonics and Applications) group and Dr. Marc Eichhorn, head of the “Lasers and Electromagnetic Technologies” division, were awarded the “NATO SET Panel Excellence Award” for their outstanding contribution to the SET 170 Task Group on “Mid-Infrared Fibre Lasers” that enhanced the visibility of the SET Panel and is a major benefit for the NATO community.

Knight of the French National Order of Merit
On the occasion of the inauguration of the new trisonic wind tunnel, Dr. Dominique Chargeleque, head of the “Flight Techniques for Projectiles” division was awarded the rank of “Knight of the French National Order of Merit.”

Group for Aeronautical Research and Technology in EUROpe (GARTEUR) Award
The international Group for Aeronautical Research and Technology in EUROpe (GARTEUR) awarded the distinction of “Eminent Member” to Dr. Patrick Gneunni during their annual conference in Seville in November 2015, in recognition of the services he has rendered to the aeronautical community.

Innovation Award
On April 22, 2015, NS3E* was granted the “Innovation Award” by the MBDA group, a prize awarded to the most promising patents. The patented innovation consisted of mixing nanostructured inert powders by motion induced by magnetic particles.

2016 Awards

International Symposium on Ballistics
Two major awards were granted to research work conducted by ISL scientists during the “International Symposium on Ballistics”, which took place in Edinburgh, UK, on May 9–13, 2016.

Rosalind & Pei Chi Chou Award
The “Rosalind & Pei Chi Chou Award,” honouring the work of eminent young researchers, was granted to Stephan Weidner, Robert Hruschka, Christian Rey, Friedrich Leopold and Friedrich Seiler for their work on “Supersonic wake flow analysis of finned projectile afterbodies at various spin rates.”

2016 Ingénieur Général Chanson Award presented to the B-SAVED team as “Innovation of the year”!
An important meeting point at Eurosatory 2016 was the ceremony for the “Ingénieur Général Chanson Award”, organised by the French Land Defence Industries Group (GiCAT) and the French Association of Land Armaments (AAT) on June 15, 2016. They attributed the Award to Dr. Pierre Raymond and Dr. Nicolas Hueber, representing the ISL Laboratory for Sensor Intelligence ELSI, for the B-SAVED concept consisting of an autonomous sensor equipped with artificial intelligence and able to detect, evaluate and make a decision in real time.

Best papers
The paper presented by the ELSI laboratory and entitled “A bioinspired approach to intelligent Unattended Ground Sensors (B-SAVED)” was awarded the first prize for the best scientific contribution at the International Conference on Artificial Intelligence and Bio-inspired Data Processing: Theory and Applications IX. This prize rewards the paper presented by Dr. Nicolas Hueber at the SPIE Symposium on Defence, Security and Sensing in Baltimore, USA, on April 21, 2015.

The oral presentation on “The Production of Energetic Nanomaterials by Spray Flash Evaporation” given by Martin Klaumünzer, Jakob Hübner and Dr. Denis Spitzer received the Best Paper Award from the World Academy of Science, Engineering and Technology during the 18th International Conference on Nanosciences and Nanotechnologies. The Committee of the 18th International Symposium on Electromagnetic Launching awarded the “Certificate of Excellence” to Dr. Stephan Hundertmark for his paper on electromagnetic launching systems. The EML Symposium took place in Wuhan, China, in October 2016.

At the SPIE Security + Defence Conference 2016, Jonathan Klein, an ISL PhD student researching at the University of Bonn, was granted the “Best Oral Paper Award” for his paper “Real-time tracking around a corner”.

*SNS* the joint laboratory founded by ISL, CNRS and the University of Strasbourg
The life cycle management of defence systems has become an increasing challenge both for the French and German Ministries of Defence. The ageing of materials that are used or stored in severe environments can indeed lead to a loss of their performance. This fact has been assessed as a critical point both for energetic systems and protective materials. Moreover, the REACH and RoHS regulations have an increasing impact on the obsolescence of products, which makes the research on substitute materials for defence applications mandatory.

However, beyond these issues, top priority is still given to the following military requirements: reduced vulnerability and enhanced performance for energetic materials and weight reduction for advanced protective or structural materials. In order to fulfill these requirements, ISL scientists have to face two main scientific challenges:

- on the one hand, they have to be able to develop new materials with a very accurate control of their physical and chemical properties, ranging from the micrometric down to the nanometric scale, as the features of these materials have a direct influence on the performance of the systems;
- on the other hand, they have to deepen their understanding of the influence of various material parameters on their intended properties.

Progress on each of these topics is to be made in parallel, as these two activities are strongly interdependent and are required for producing materials with enhanced properties. In order to tackle these issues, ISL has been developing strong research activities in three scientific domains:
- materials manufacturing processes,
- materials characterisation,
- modelling related to the two previous domains.

The Spray Flash Evaporation (SFE) technique is a brilliant example of the work performed at ISL in the field of materials manufacturing processes (see p. 36).
FLIGHT TECHNIQUES FOR PROJECTILES

Research on guided ammunition requires a deep knowledge of the prototype building, integration and the gun-hardening of various communication systems, sensors and their associated electronics. ISL has at its disposal different wind tunnels and has the possibility of performing free-flight tests at the ISL proving ground. These important assets allow the testing and development of the necessary technology bricks for guided ammunition. Studies on measurement and navigation units have been conducted, based on low-cost MEMS (Micro-Electro-Mechanical Systems: magnetometers, accelerometers, gyros) with and without GNSS (Global Navigation Satellite System).

A lot of progress has been made, in particular in mastering the models of the various sensors (magnetometers, accelerometers, gyros and GNSS receivers) and in the calibration of the parameters of these models in the laboratory and in flight at short range at our open range site. These pre-tests are beneficial and necessary to prepare the long-range firings at the proving grounds of Bourges (France) and Meppen (Germany) (see pp. 32–33).

Innovative aerodynamic architectures and guidance and control solutions

Several concepts have been evaluated. The first results are very promising, e.g. for increasing the range of guided projectiles. A significant amount of work remains to be done to obtain a more reliable performance level and to optimise them. The new trisonic wind tunnel will greatly contribute to the achievement of this goal.

Bidirectional communication and telemetry systems

Noticeable achievements have been accomplished. Reconfigurable conformal phased array antennas have been designed as well as small antennas with metamaterials. This work will be continued for the design of GNSS antennas (among others) that are resistant to jamming and spoofing (see pp. 33–34).

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The “Laser and Electromagnetic Technologies” division focuses on basic and applied research necessary to realise the electromagnetic (EM) weapon and protection systems of the future: high-energy and countermeasure laser sources, EM launchers and various EM effectors. As a result of the complexity of the technologies involved and due to military boundary conditions to be respected, research has to address, study and evaluate all the important aspects of these systems, including the specific energy supply chain, from the component level up to technology demonstrators.

Lasers are becoming more and more important for military applications: high-energy “eye-safe” lasers delivering sufficient energy to a target for close-in defence against threats such as mortars, etc., and special lasers for countermeasures designed to jam and damage optical systems (see p. 29). The research efforts focus on the realisation of novel laser sources.

Considerable technical progress has been achieved in the field of railgun projectile development and EM launcher scaling towards long-range artillery applications. The cross-cutting character of these activities will be found in the “MELIAS” and “ELMAS” sections of this report (see pp. 26–28).

Addressing the high current, voltage and power switching rates required, in a parameter range not covered by industrial applications, the research on semiconductor components has focused on silicon carbide devices. Especially SiC thyristors and PIN diodes are investigated, to promote significant improvements in the size, weight and power for pulsed power generators.
In contrast to the other ISL scientific divisions, the structure and organisation of the “Protection Technologies, Security, Situational Awareness” division are application-oriented and even more interdisciplinary. Its work is dedicated to improving the survivability of defence/security forces and civilians in a hostile environment characterised both by the presence of energetic materials, ballistic threats and by upcoming directed energy weapons.

An important part of the research activities thus consists of a comprehensive analysis of threats, which is a crucial step towards providing suitable protection solutions. Furthermore, an ongoing analysis of known and emerging threats is necessary to guarantee that this work will stay in phase not only with today’s but also with tomorrow’s operational needs. For instance, we also investigate the effects of high-energy lasers, as they will certainly become a component to be considered in future scenarios.

Action is to be taken at different levels for the protection of the soldier. The first step is to detect threats at a safe distance to enhance the situational awareness and the global perception of threats and targets on the battlefield (electronic detection systems for enhancing the soldier’s natural visual and acoustic senses). After detection, a confirmation at the recognition or identification level by using advanced optical and acoustic sensors is necessary. After stand-off detection, recognition or identification, defeating the threat has to be considered by means of destruction, neutralisation or mitigation techniques. The last stage addresses physical protection. Our research activities are two-fold: on the one hand, the objective is to contribute to the protection of mobile platforms on land, in the air and at sea; on the other hand, the research efforts focus on the protection systems of the personnel.
Electromagnetic railguns can accelerate heavy projectiles to velocities above 2000 m/s. This exceeds the limits of conventional guns, paving the way for new military and civilian applications such as hypersonic weapons or space launch systems. ISL has become the leading European actor in this game-changing technology.

From a military point of view, railguns will offer significant superiority over conventional guns thanks to hypersonic muzzle velocities (Mach 5 to 7), resulting in shorter time to the target and extended range (up to 200 km). With no propellant required on board the platform, they will provide increased safety and have more space for magazines. A lower cost per engagement, compared with missiles of comparable range, will also be achieved.

With a view to combining its long-standing experience in the fields of electromagnetic acceleration and aeroballistics, ISL has initiated the ElectricMagnetic Artillery System (ELMAS) project which focuses on the military applications of railgun systems. The objective of the project is to design and develop the critical system components and to investigate the system performance at the ISL proving ground, combining electromagnetic acceleration with free-flight experiments.

The word “system” is here of prime importance since it covers not only the railgun and the related high pulsed power supply but also the ammunition (projectile, sabot, armature, payload and on-board electronics), the platform integration constraints (in particular, electromagnetic radiation hazards to personnel, equipment and ordnance) and the concepts of use for land and naval operations (close-in defence, anti-surface warfare, anti-air warfare and land attack).

Improving railgun technology

Key aspects for the realisation of such a high-power weapon are large muzzle velocities, high launch efficiency, mega-ampere current amplitudes, launch package design and barrel durability.

Recently, the research conducted at ISL has concentrated on improving launch efficiency. The careful designing of the armature – the part of the projectile which is accelerated by magnetic forces – allowed ISL to successfully carry out experiments attaining muzzle velocities of 3100 m/s with a launch efficiency of more than 40%. This result is a world record as far as the open literature is concerned.

The next step consisted in developing a launch package including a sabot protecting the projectile during launch. The X-ray picture shows the launch package during free flight, just after leaving the 40-mm square calibre railgun. It can be observed that the sabot is opening and freeing the hypervelocity projectile (Fig. 1).

The long-range scenario requires launchers with larger calibres, due to aerodynamic considerations. Therefore, a next-generation 60-mm square calibre railgun has been designed. The launcher with an acceleration length of 6 m is designed to achieve kinetic energies above 3 MJ. A 2-m-long prototype is currently being tested at the railgun research facility at ISL (Fig. 2).

XRAM generators for electromagnetic launch

Electromagnetic launchers require electrical energy at unique gigawatt power and megajoule energy levels. ISL’s research is focusing on inductive pulsed-power supplies with improved size, weight and power (SWaP) ratings. Combined with batteries, inductors offer advantages over capacitors due to their higher energy density and favourable power conversion (Fig. 3). Within the framework of the CIGAR project, ISL is aiming to build a 1-MJ inductive power supply demonstrator based on the XRAM topology with patented opening switch circuitry. The demonstrator aims to supply a laboratory scale railgun.

In order to charge the XRAM generator, a battery consisting of 200 high-power LiFePO4 cells was developed and realised and is now available for experiments requiring time-limited DC currents in the kA range. Due to the modular and flexible set-up, the nominal voltage and the nominal inner DC resistance range from 64 to 640 V and from 3.25 to 260 mΩ, respectively. The battery features a specific in-house-developed monitoring system and two opening switches to ensure safe operation under megawatt conditions.

The 1-MJ XRAM generator design provides a toroidal architecture with 20 identical segments (Fig. 4) enabling a twentyfold current amplification. A prototype coil segment with a special D-shaped cross-section (Fig. 5) was developed and successfully tested with respect to its electrical and mechanical performance. Several thyristor types were investigated for their switching performance and current flow. It was demonstrated that the switching assembly is capable of interrupting a current of 10 kA per device.

The paper covers the ELMAS heralding railgun systems project and the XRAM generator development.
Considerable progress recently made in the field of solid-state lasers will allow the development and use of laser weapons in the near future. When using high-energy lasers in military operations, not only technical aspects – such as the generation of high laser power with good beam quality for optimum long-distance focusing – have to be considered but also legal aspects, such as the international prohibition of blinding laser weapons. In that respect, only so-called “eye-safe” laser weapons may be compliant with protocol IV of the 1980 “Convention on certain conventional weapons”.

Within the scope of the MELIAS project, ISL has studied a very promising laser technology in the “eye-safe” wavelength region: the erbium:YAG heat-capacity laser. This type of laser is characterised by a compact design, a simple and robust technology and a scaling law which, in principle, allows the generation of a laser power far beyond 100 kW at small volumes. The unique feature of the laser is its operating scheme: a laser medium (crystal or ceramic) is used for one shot, lasting for about 3 to 5 s without any cooling, it is then replaced by a cold medium. Several shots without cooling may be performed, using the revolver technology designed at ISL. Alternatively, by adding a special cooling system to the revolver, the laser should be able to operate in a repetitive, continuous mode.

After two laboratory set-ups, MELIAS I and MELIAS II, which proved the effectiveness of the working principle of this kind of laser, the upscaled MELIAS II+ is under construction at ISL. The aim of MELIAS II+ is to reach a power of up to 30 kW for several seconds.

**Effect-based design**

Laser-matter interaction can be regarded as the counterpart to projectile-based weapons in terms of ballistics, owing to the unique capability of laser beams to carry energy at the speed of light over large distances. Modeling becomes increasingly important to minimise the cost of experimental series, to quickly adapt them to changing threats or to the development of novel materials. In the case of laser-matter interaction, merely considering a static sample while ignoring all the other boundary conditions (such as, for example, the proper movement of the sample and the surrounding air flow), leads to results that take into account only a small part of reality. ISL has developed customised modeling codes as well as specific experimental set-ups that include such parameters, so that realistic operational conditions are provided. Fig. 1 shows the significant difference in the effects of laser irradiation on a metallic sample when the air flow is taken into account and when it is not, while all the other parameters are maintained. Taking into consideration the rotation of a sample drastically changes the heat transfer into the sample.

One of the main activities of ISL’s laser research is the design of beyond-state-of-the-art highly versatile laser sources emitting in the mid-infrared (mid-IR) region, that have to fulfill the requirements for optronic countermeasure applications. Innovative architectures allow the restrictive size, weight and power (SWaP) requirements to be met. ISL teams take part in field trials and measurement campaigns with current state-of-the-art ruggedised lasers, another mission that enables an assessment strategy to be elaborated and infrared countermeasures to be determined both for the French and German MoDs.

Optical fibres are expected to allow the next step of improvement to be undertaken. Fibre lasers emitting radiation at 2 µm are of particular interest. Their radiation is effectively down-converted within an optical parametric oscillator (OPO) or within nonlinear fibres to obtain powerful radiation in the mid-IR region. New fibre designs and compositions were conceived, then built up with partners and successfully implemented.

Fibered components were developed with partners and implemented into ISL set-ups, to close the gap between the required 2-µm fibered components and the existing commercial component toolbox and to enable the realisation of high-power all-fibre laser systems at 2 µm. A record average output power of 6.5 W was generated by a mid-IR ZnGeP$_2$ (ZGP) OPO pumped directly by a 2-µm Q-switched single-oscillator fibre laser. The generation of a supercontinuum in nonlinear optical fibres was studied to fully cover the mid-IR range. This bandwidth is extended to beyond 4.2 µm with an output power of 78 W and was further broadened to reach 4.9 µm.

A high-energy mid-IR ZGP OPO based on the ISL non-planar Fractional-Image-Rotation-Enhancement (FIRE) resonator pumped by a 2.05-µm Ho$^{3+}$:YLF laser delivered up to 120 mJ of pulse energy in a rotationally symmetric beam at a 1-Hz repetition rate within the framework of a NATO collaboration.

Joint trials on a Directional InfraRed CounterMeasure (DIRCM) laser source were carried out at a distance of about 2 km to evaluate current source technologies and their use in DIRCM systems for fighting incoming threats (Fig. 1 and Fig. 2).
The project “Optical and Acoustic System for Security and Surveillance (OASyS²)” is an ISL internal project aiming to coordinate and cross-connect the research activities of different ISL groups in the fields of sensor technologies, surveillance and countermeasure techniques. The OASyS² project focuses on the detection, localisation and identification of small unmanned aerial vehicles (UAVs) as well as on the investigation of countermeasures for their neutralisation.

UAVs are increasingly becoming a serious threat in the context of civilian and military scenarios. Recent developments in UAV technologies tend to bring autonomous, highly agile and versatile unmanned aerial vehicles onto the market (Fig. 1). These UAVs can be used for spying operations (data collection for mission planning or infringement of privacy) as well as for transporting material (smuggling, flying improvised explosive devices). Within the framework of the OASyS² project, ISL develops technology building blocks for the detection and identification of UAVs to prepare countermeasures, leveraging existing ISL know-how. Further on, additional technologies provided by external partners will be investigated.

The ISL detection technology is based on acoustic antenna arrays which were originally developed for sniper detection. First field trials have shown that the acoustic detection of UAVs (rotary wings) is possible, due to the distinctive acoustic signature caused by fast rotating propellers. A single antenna offers an estimation of the direction of the sound source in azimuth and elevation (Fig. 2). A distance estimation cannot be given by a single acoustic antenna, due to the continuous nature of the acoustic signal. ISL is currently working on a network of acoustic antennas which can be distributed, for instance, as unattended ground sensors. Thus, UAVs will be located by triangulation.

The precise localisation and identification of UAVs are achieved by optical sensing (Fig. 3). Here, both passive and active imaging are investigated. While passive imaging can provide high-resolution colour images of the target, active imaging can be used for ranging and for increasing the target-to-background contrast. By gating out the background and foreground, laser gated viewing allows the operator’s attention to focus only on the target itself. Thus, the impact of textured environments on the identification performance can be neglected. UAVs can be identified by the operator at distances up to 1 km with the present set-up and even under harsh environmental conditions, such as fog, smoke and heavy rain.

ISL is assessing the potential of laser-based countermeasures by studying the laser vulnerability of various structural materials, such as plastics, composites, etc. Vital functional devices, such as battery packs, electronic control and communication units, are also investigated. Extensive laboratory experimentation is necessary to address the degradation processes and assess the damage thresholds. This research is complemented by a strong modelling effort in order to be able to simulate the thermal effects induced by beam coupling. The goal is then to run simulation tests to tune the laser weapon tactics to fit a given scenario.
AFFORDABLE NAVIGATION FOR GUIDED AMMUNITION

Navigation units based on low-cost MEMS (Micro-Electro-Mechanical Systems: magnetometers, accelerometers, gyros) with or without GNSS

The objective of this research activity is to develop a gun-hardened inertial measurement unit based on ITAR-free, low-cost, off-the-shelf components for guided munitions. These studies involve the design of on-board electronics that include sensors, a real-time computing unit and a radio frequency telecommunication system. This research work also addresses the development of dedicated navigation algorithms that take into account the modelling of the sensor behaviour under firing conditions and a simplified 6 DoF (Degrees of Freedom) ballistic model of the projectile.

G-hardening tests on selected sensors which are compatible with ammunition applications have been conducted in ISL’s unique SIBREF (Soft InBore REcovery Facility) bench. Several sources of magnetometers, accelerometers, gyros and GNSS (Global Navigation Satellite System) receivers were identified and successfully tested. An instrumented fuse was developed for a long-range firing campaign with 156-mm projectiles for data acquisition and component testing. It integrates a new telemetry system with a 2-Mbps transmitter and a computing unit that allows the collection of sensor and GNSS signals as well as radio frame conditioning. The Electro-Magnetic Compatibility (EMC) between the telemetry and GNSS systems has also been investigated. Sensor models and their related calibration processes are developed in order to assess an accurate sensor response under highly dynamic motion conditions of the projectile (roll rate up to 1000 Hz and high acceleration). The study includes the particular projectile environment of ferromagnetic material. In particular, the spin-induced magnetic field distortion is investigated and can be compensated with precision for roll rates up to 1 kHz. The validation of these models by using free-flight tests is being carried out at the ISL proving ground. The real-time estimation of the roll position of a spin-stabilised projectile was demonstrated at 760 Hz with an RMS error of less than 2 degrees.

The data processing of a “Basic Finner” firing campaign in 2014 showed that it is possible to estimate the angle of attack and the side-slip angle of a projectile only by means of magnetometers and accelerometers. By making use of the redundancy in the measured data, the sensor models and the attitude estimation algorithm can be validated. The first successful firings of projectiles equipped with gyros were carried out at the end of 2015 and a good agreement with the magnetometer and accelerometer signals was found. Figure 1 shows the instrumentation of a Basic Finner projectile used for these tests.

Spin-stabilised guided concepts require that the guidance fuse containing all the GNC (Guidance, Navigation, Control) components and the steering control surfaces should be decoupled in rotation from the main body at the top of the trajectory. A specific front-part decoupled fuse architecture was recently designed (Fig. 2) and tested at the ISL proving ground.

Specially developed navigation algorithms take into account the projectile flight dynamics, as well as the in-flight sensor calibration. Various scenarios (with and without GNSS) and various types of projectiles (fin-stabilised projectiles with or without a front-part decoupled fuse) are being considered, and the precision of the navigation solutions is currently being investigated.

Bidirectional communication

Future guided ammunition will require more powerful telemetry systems to transmit the on-board sensor data of the instrumented projectiles. An up-link is necessary to initialise the navigation units, to transmit the control commands or to update the target data. Especially in the case of small-calibre projectile applications, the size of the different antennas must be reduced. Therefore, antenna structures are investigated, based on meta-materials which either allow the available bandwidth to be increased or the size of the antenna structures to be decreased.

Meta-surface cavity antennas

Cavity antennas based on meta-materials are an interesting technology for small-projectile applications. However, the antenna structure can only be miniaturised down to a limit that is determined by the dimension of the antenna structure with respect to the wavelength. Below that limit the available bandwidth is reduced in such a way that the antenna does not work any longer. But meta materials may lower that limit. Several classical patch antennas and antennas based on meta-materials of different sizes have been numerically simulated before being built. The bandwidth results for different circular patch and meta-material antennas at 2.3 GHz are summarised in the table below.

<table>
<thead>
<tr>
<th>Ø</th>
<th>Patch</th>
<th>Meta-material</th>
</tr>
</thead>
<tbody>
<tr>
<td>32 mm</td>
<td>64 MHz</td>
<td>simulation measured</td>
</tr>
<tr>
<td>20 mm</td>
<td>52 MHz</td>
<td>simulation measured</td>
</tr>
<tr>
<td>16 mm</td>
<td>not working</td>
<td>20 MHz</td>
</tr>
<tr>
<td>16 mm</td>
<td>not working</td>
<td>19.8 MHz</td>
</tr>
</tbody>
</table>

As can be seen, a classical patch antenna, whose diameter is reduced to 20 mm, does not work any longer, whereas a meta-material antenna with a diameter of 16 mm still has a bandwidth of 22 MHz (Fig. 3).

Reconfigurable conformal antenna arrays are investigated for projectiles. The goal is to make them less sensitive to the jamming of Global Navigation Satellite System (GNSS) devices but also to enhance the performance of the communication links for long-range applications.
Reconfigurable conformal antenna arrays

Several prototypes of conformal antenna arrays have been investigated with regard to their integration into a projectile fuse. Figure 4 shows a 12-element conical antenna array made of four linear sub-arrays with 3 probe-fed radiating elements per sub-array. A prototype was designed and validated by numerical simulation before being built. The measured radiation characteristics of the elementary radiating element (active pattern) and of the sub-array are in good agreement with the simulation results. The proposed array configuration allows the rotation and steering of the antenna beam in order to ensure effective point-to-point communication.

The individual elements have a bandwidth of 180 MHz each. In order to keep the radiation pattern in a given direction independent of the projectile spin (e.g., a GNSS antenna should only look upwards to the sky in order to be less sensitive to jammers), the individual sub-arrays can be switched on and off with respect to the rotation. Alternatively, phase shifters are used to keep the main beam of an array always oriented in the desired direction towards the receiving station. This increases the available communication bandwidth and/or the communication distance for telemetry applications.

Look around the corner

Non-line-of-sight imaging – a breakthrough emerging technology

The challenge consists of reconstructing a hidden scene by sensing and by analysing the information emitted by scattered photons (schematically depicted in Fig. 1).

A collimated laser pulse illuminates at a non-visible wavelength a spot on a scattering surface such as ceilings. The light is diffusely reflected into a hemispherical space illuminating a hidden scenario. Then, the light is reflected off the surfaces of the object and bounces off the wall once more. Due to multiple scattering, the detected light carries no information for performing direct imaging of the scene but it contains enough valuable information for computational imaging.

It is possible to locate the hidden reflection source in a three-dimensional space, i.e. “look around the corner”. Our algorithm analyses the intensity distribution of the back-reflected light which is recorded by a camera. Then, the algorithm calculates a synthetic intensity distribution by 3D rendering of the light propagation in the scene and is looking for an optimised synthetic solution. As a result the target position can be plotted as a 3D scene reconstruction. In the past year, the pertinence of our approach was verified and the imaging of scattered photons was experimentally demonstrated. To further extend this work, new approaches to sensing and processing are being investigated in the context of an international collaboration.

A novel computational method by tracking known objects is being studied illustrated in fig. 2. The algorithm compares the captured image data (intensity, time-of-flight map, etc.) with the result of the synthetic rendering of the scene. After applying several optimisation steps, this algorithm delivers reliable 6-degree-of-freedom estimations, i.e. translation in the x-, y- and z-axes and corresponding rotation. Owing to massive parallel processing, this approach works at a near-real-time video rate.
**SFE: SPRAY FLASH EVAPORATION**

Efficient production of nanometric explosives

Aims and defence needs fulfilled

The interest in energetic nanomaterials such as explosives or priming nanocomposite formulations is constantly growing. It currently fulfills high applicative needs as these nanomaterials allow enhanced performances such as improved reactivity, reduction of the critical diameter for detonation (thereby reducing the amount of explosives needed to propagate a detonation), enhanced mechanical effects and reduced sensitivity to mechanical stress. The production of nanometric explosive particles is rather a challenge compared to other materials, for which nanostructuration is fairly easy to achieve, due to the existence of adapted precursors. Laboratories worldwide explore different techniques such as sol-gel methods, the Rapid Expansion of Supercritical Solutions (RESS), or even antisolvent techniques. None of these methods permits the production of nanometric explosives in sufficient quantity and with reproducible quality for industrial applications.

**SFE (Spray Flash Evaporation): a versatile process**

Pioneering studies on spray systems were started by the NS3E laboratory at ISL in 2006. A spray technique was considered, due to its continuous character which was essential for reaching industrial amounts with maximum safety and reproducibility. Different set-ups were conceived and designed at ISL. Until now, all of them have followed the same principle. At first, the explosive or mixture of explosives to be nanocrystallised is dissolved in a low-boiling organic solvent. In general, the concentration of each compound is comprised between 1 and 10 wt% at room temperature. Then the solution is pressurised to 40 bar, thus avoiding any evaporation of the solvent and storing energy in the system in this way. Next, the solution is expanded through a heated hollow cone nozzle into a primary vacuum chamber. The nozzle is heated at temperatures between 130°C and 160°C while the vacuum within the evaporation chamber is increased from 5 to 20 mbar. The extreme pressure drop, from the high-pressure to the low-pressure zone, and the subsequent temperature drop instantaneously induce the evaporation and subsequent crystallisation of the compound that has been dissolved in the pristine solution. After its crystallisation, the product is trapped in a cyclone, a filter, or an electrical precipitator (see Fig. 1a).

Its very high versatility positively differentiates the SFE process from the other techniques mentioned. Diverse hierarchical-structured products can be formed, depending on pure precursors or mixtures, and, in the latter case, on the intermolecular interactions between different molecules, as shown in figure 1b. These structures arise as pure nano- or submicron-sized particles or even crystalline nanocomposites, with dissociated or core-shell particles. They can also be semi-amorphous or totally amorphous. In the case of intense intermolecular bonds, nano- or submicron-sized cocrystals are formed.

Starting from a horizontal pilot plant which did not integrate the possibility of online crystallisation mechanism studies, a further system was built to produce sufficient nanostructured hexolite for the synthesis of the smallest nanodiamonds ever synthesised worldwide. This was another breakthrough achieved by the NS3E laboratory. These nanodiamonds are promising candidates for advanced materials in the field of medical diagnostics or optical limitation, for example. A further attempt was then made to study the crystallisation and nano-cocrystallisation mechanisms by conceiving and designing a vertical pilot plant with quartz windows placed opposite each other. The latter geometry allows online metrology to be used to investigate the evolution of droplet formation and particle crystallisation.

The fourth-generation pilot plant will integrate some novel modifications in order to face the challenge of understanding the material production mechanism.
explosive. This challenge could be met at ISL for the first time worldwide.

The 100 g/h breakthrough
Another major challenge was addressed during the last two years at ISL. It concerned the scale-up of SFE. Driven by the need to produce sufficient amounts of nanostructured hexolite (RDX/TNT 60/40) at NS3E, the SFE process was upscaled by designing a larger evaporation chamber in which a high flow rate nozzle was mounted (Fig. 4). A powerful vacuum pump was subsequently added to the pilot plant in order to maintain the primary vacuum of the evaporation chamber within the range from 5 to 20 mbar. These improvements and some others led to a production rate of up to 100 g of nanostructured hexolite per hour. Nano-RDX was also produced with a comparable production capacity. This paves the way for a further extension to meet industrial demand.

Outlook and future scientific challenges
The first challenge has been the increase in the production capacity and the broadening of the range of products. Basic research will now be intensified with respect to the understanding of the crystallisation mechanism that takes place inside the SFE reactor under thermodynamical conditions. For this purpose, several online metrology methods were conceived in the laboratory in order to assess nucleation and growth kinetics during the process itself. First measurements made it possible to determine the size and velocity of the spray droplets inside the evaporation chamber. Other techniques developed by NS3E will also provide online thermal and dynamical spectra of the products obtained. To investigate the nucleation process in detail on the whole production time scale other attempts will be made by using synchrotron radiation at external facilities.

To broaden the scope of SFE to other products and applications, extensive and fundamental research on the characterisation of the pure and/or hierarchical-nanostructured composites will be required. All the methods for online and post-elaboration characterisation, combined with the fourth novel SFE nanocrystalliser generation, will increase the possibility of elaborating high-performance nanostructured explosives and propellants for today’s needs and for future applications.
Spark-Plasma-Sintering

Test section of ISL’s trisonic wind tunnel

Insight into high pulsed-power supply activities

A new analytical set-up for investigating protection structures
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