EPS Forum Physics and Society
Physics for society in the horizon 2050

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with input from EPS Divisions and Groups

I. Introduction

Science begins when someone raises a general question and sets about answering it by methodical investigation, including and combining experimentation and logical argumentation. Such scientific action spawns understanding on the workings of the world in its broadest sense and, therefore, the power of prediction the behaviour of different bodies and objects. The corollaries are significant practical advantages - ranging from agriculture to medical applications. The dawn of science is therefore as old as the dawn of man as we know it – the mastery of fire, tools, agriculture, and, later, the isolation of alloys and pure metals were, as such, great scientific advances. These were to be followed by the inevitable questions, born out of sole curiosity, regarding consciousness, the place of man in the universe and the workings of the cosmos. Thus, one of the first problems to be tackled truly scientifically by ancient historical cultures was to conceive explanations of the seasons and of how heavenly bodies move. Without this initial curiosity, on which our scientific and technological knowledge are based, human beings would be radically different. The build-up of knowledge concerning the workings of the distant universe and the world at hand on one side, and the properties and behaviour of materials on the other have lead, in the second half of the XVIIIth century, to the advent of the fecund scientific-technological alliance expressed by the industrial revolution. The harnessing of electromagnetism and its phenomenal stream of applications followed in the course of the XIXth century. The huge social impact of both events is unrivalled - it is difficult to think of any political, religious or economical doctrine that has brought about such radical and robust changes in society.

Creativity and imagination play a vital role in the development of science, insofar as one of the main objectives of science is to shape (imagine) the future. Scientific knowledge and understanding springs from such creative, curiosity-driven research, which has proven itself to be the only road to new paradigms and true innovation. Moreover, one should not overlook the cultural impact of scientific research, training through research and science-based education. It is the principal method by which members of society mature to critical, rational, and independently thinking citizens. A modern developed scientific society must, therefore, nurture a strong scientific sector, both in education and research, in order to address its technological and societal challenges.

Although the quest for knowledge in itself is not necessarily susceptible to ethical evaluation, science abandons its ethical neutrality when it addresses the way in which knowledge is generated, and when one considers the impact of its technological applications on individuals and society. This is particularly clear in health research, where the interests of science, society and corporations should never prevail over individual liberties and wellbeing, or research for sustainable development, where the desires of individuals should not prevail over the common good of society and humanity (which, in itself, has to be the object of scientific investigation and debate). Furthermore, the development of artificial intelligence will lead us through a fascinating landscape of development as well as ethical considerations. Consequently, science as a whole is not ethically neutral. Quoting Berthold Brecht in his play “Life of Galileo Galilei”, *should people dedicated to science develop something like a Hippocratic Oath with the promise of using Science solely for the benefit of mankind?* Science should aim to raise standards of living at global scale, requiring long-term perspectives on international cooperation with investment in research, education and sustained development in the global crossroad of energy sources.

The present EPS action will address the social dimension of science and the grand challenges in Physics to bring radical changes on developed societies, to raise standards of living at global scale and to provide basic understanding of nature in the Horizon 2050. This action will be developed within the framework of the EPS / Forum Physics and Society activities in the period 2018 – 2019.

II. Topics

1. **Physics as global human enterprise for understanding nature:**

    1.1. Physics on the smallest scales
    - 1.1.1. Particle physics: physics beyond the Standard Model
    - 1.1.2. Nuclear physics: origin of matter in the visible universe
    - 1.1.3. Quantum gravity: an unfinished revolution

    1.2. Physics on the largest scales
    - 1.2.1. What is the universe made of: searching for dark energy / matter
    - 1.2.2. A gravitational universe: black holes and gravitation waves
    - 1.2.3. Stars, the Sun and planetary systems as physics laboratories

    1.3. Understanding complexity
    - 1.3.1. Quantum many body systems and emerging phenomena
    - 1.3.2. More is different: the search for new materials
    - 1.3.3. High temperature superconductors: physics and applications.
    - 1.3.4. Topological states and novel quantum states
    - 1.3.5. Second Quantum revolution: quantum computing and information
    - 1.3.6. Manipulating photons and atoms: photonics and nanophysics
    - 1.3.7. Extreme light
    - 1.3.8. Systems with numerous degrees of freedom

    1.4. Physics for understanding life
    - 1.4.1. Searching for life in the universe: What is our place in the universe?
    - 1.4.2. Artificial intelligence: What is the nature of human mind?
    - 1.4.3. Artificial life: sustainable self-replicating systems
    - 1.4.4. Where physics meets biology: Is there new Physics in living matter?
    - 1.4.5. The emergence of life: the Sun-Earth connection

2. **Physics developments to tackling major issues directly affecting the lives of citizens:**

    2.1. Physics for health science
    - 2.1.1. Light for health
    - 2.1.2. Accelerators for health
    - 2.1.3. Magnetism for health
    - 2.1.4. High-resolution imaging
    - 2.1.5. Bionics and robotics
    - 2.1.6. Artificial tissues and self-repairing systems
    - 2.1.7. Plasmas and medicine
    - 2.1.8. Further applications

    2.2. Physics for sustainable development and clean energy
    - 2.2.1. Physics of earth and climate
    - 2.2.2. Physics fields with relevance for energy technologies: strategies for energy conversion and storage

2.2.3. Green cities: actions on climate change addressing the development of green transport

2.3. Physics for secure and efficient societies

2.3.1. Environmental safety
2.3.2. Cyber security: networking and grid power modeling
2.3.3. information and communication technologies
2.3.4. Bio-inspired technologies
2.3.5. Sensors and applications
2.3.6. Understanding and predicting space weather
2.3.7. Large-scale complex socio-technical systems and their interactions

III. Description of topics

1. PHYSICS AS GLOBAL HUMAN ENTERPRISE FOR UNDERSTANDING NATURE

1.1 PHYSICS ON THE SMALLEST SCALES

1.1.1. Particle physics: physics beyond the Standard Model

General overview

High-energy particle beams can be collided to create new particles that do not exist in the everyday world but tell us about the building blocks of the universe. This is the goal of the LHC programme.

The Standard Model of particle physics agrees very well with experiment, but many important questions remain unanswered [e.g. J. Ellis, Phil. Trans. Soc. A (2012) 370, 818], including: Hoes does one understand the number of species of matter particles and how do they mix?, What is the origin of the difference between matter and antimatter and is it related with the origin of the matter in the Universe?, How does one quantize gravity?

Challenges and opportunities

Towards grand unification theory: is the string theory the answer?, are there fundamental particles that have not yet been observed?.

1.1.2. Nuclear physics: origin of matter in the visible universe

General overview

The physics of nucleus is fundamental to our understanding of the universe and at the same time, intertwined in the fabric of our lives. Important questions addressed in this field concern the properties of the quark soup formed after the Big Bang giving rise to the formation of protons and neutrons and the evolution of chemical elements. New isotopes and elements are created in the laboratories which have only existed in properties of the quark soup formed after the Big Bang giving rise to the formation stellar explosions or in the merger of neutron stars. The science questions are thus: how visible matter come into being and how does it evolve? How does subatomic matter organize itself and what phenomena emerge?

Challenges and opportunities

- ✓ Towards the understating of the formation of strongly interacting matter after the big bang: how is the internal structure of nucleons? What is the origin of elements and of nuclear binding?
- ✓ How does the development of new tools and accelerators used for nuclear physics research find broad applications in industry, medicine and national security [see 2.1.2]?

1.1.3. Quantum gravity

General overview

What happens to classical general relativity at the extreme short-distance Planck scale?

Challenges and opportunities

How to search for quantum gravity?

1.2 PHYSICS ON THE LARGEST SCALES

1.2.1. **What is the universe made of?: searching for dark energy / matter**

General overview:

Description of physics fields with relevance on the search for dark energy / matter to clarify what is the universe made of:

- ✓ **Dark matter** has not been directly observed, but it seems to outweigh visible matter making up about 30% of the universe. Its existence and properties are inferred from its gravitational effects such as the motions of visible matter, its influence on the universe's large-scale structure and its effects in the cosmic microwave background.
- ✓ **Dark energy.** Dark energy makes up approximately 70% of the universe. It is distributed evenly throughout the universe, not only in space but also in time. The even distribution means that dark energy does not have any local gravitational effects, but rather a global effect on the universe evolution as a whole.

Challenges and opportunities:

Description of challenges and opportunities in the Horizon 2050:

- ✓ **Search for dark matter particles:** One idea is that it could contain "supersymmetric particles" – hypothesized particles that are partners to those already known in the Standard Model. Experiments at the Large Hadron Collider (LHC) may provide more direct clues about dark matter.
  Dark matter particles could be in the form of Weakly interacting massive particles (WIMPs) that can be detected by looking for rare interactions via nuclear recoils in a liquid xenon target chamber (XENON1T mission at the Gran Sasso laboratory)
- ✓ **Dark energy**: Space missions and Earth-based telescopes will join the chase. Is it possible to snare dark energy in the lab?. Does dark energy really exist?

1.2.2. **A gravitational universe: black holes and gravitational waves**

General overview

Gravity or gravitation is a natural phenomenon by which all things with energy are brought toward one another, including stars, planets, galaxies and even light and sub-atomic particles. Gravity is most accurately described by the general theory of relativity, which describes gravity not as a force but as a consequence of the curvature of space-time and resulting in gravitational time dilation.

- ✓ **Gravitational waves and black holes.** Gravitational-wave detections provide physicists with the means to answer key scientific questions, such as: What are the properties of gravitational waves? Is general relativity still valid under strong-gravity conditions? Are nature's black holes the black holes of general relativity? How does matter behave under extremes of density and pressure? What happens when a massive star collapses? How do compact binary stars form and evolve, and what can they tell us about the history of star formation rates in the Universe?

Challenges and opportunities

Description of challenges and opportunities in the Horizon 2050

- ✓ **Detecting gravitational waves on earth**. LIGO has detected high frequency gravitational waves – such as those emanating from stellar black holes merging – but it has trouble detecting low frequency gravitational waves. A space-based interferometer will detect low frequency events – such as the mergers of supermassive black holes at the center of galaxies.

- ✓ **Detecting gravitational waves in space**. The LISA Pathfinder mission (ESA) has shown that it is possible to achieve the measurement precision needed for detecting gravitational waves in space. LISA will explore a completely different region of the gravitational wave spectrum and inform us about supermassive black hole mergers and other astrophysical phenomena inaccessible to LIGO.

1.2.3. **Stars, the Sun and planetary systems as physics laboratories**

General overview:

The Sun is the star closest to us, so it is our most accessible stellar laboratory. Solar physics and heliophysics study a variety of processes involving fully or partially plasmas (the plasma is the fourth state of matter, after solids, fluids and gases), actions of magnetic field generation (dynamo), magnetic reconnection, turbulence, shocks and related physics, energetic particle transport and acceleration, plasma instabilities and other relevant, fundamental astrophysical processes. For example, direct tracking of plasma waves in the solar atmosphere (i.e., Alfvén, magnetosonic, acoustic, etc.) attests to how the Sun can be exploited to advance plasma physics. The main science questions are:

- ✓ How does the solar activity, in particular the magnetic field generating dynamo, work?
- ✓ How does a cool star such as the Sun drive and sustain its hot outer atmosphere?
- ✓ How does the Sun connect to its influence sphere, the heliosphere?

Description of challenges and opportunities in the Horizon 2050:

The Sun is the only star where we can resolve structure and dynamics in its atmosphere, on its surface, and also indirectly infer them in its interior, at many of the scales relevant for the central physical processes. In brief, the proximity of our star upgrades its study to the only stepping stone we have in order to understand the fundamental principles that apply throughout the Universe, at least at stellar scales. This is our goal, therefore, in studying the Sun and heliosphere: access and understand our adjacent universe in order to make sense of what surrounds us at much larger spatial scales.

1.3 UNDERSTANDING COMPLEXITY

1.3.1 Quantum many body systems and emerging phenomena

The development of theoretical and expermental approaches for understanding many-body interactions in both “soft” and “hard” condensed matter, but also in dilute matter, atomic and molecular systems, as well as in atomic nuclei, remains one of the key challenges in physics today. A proper description of interactions and interparticle correlations is key to the understanding of the system ground- and excited states, as well as modern spectroscopies of these states, scattering, and collisions. Beyond phenomenology, the adequate description of quantum many-body phenomena will allow the understanding of emergent states of matter and new physics associated with these.

Recent advances have concerned novel types of charge and spin order, new magnetic and superconductive systems [see 1.3.3], and multiferroic systems, the switching between different orders by tuning a parameter (e.g. pressure, density, electronic excitation by radiation) but also the absence of order in a number key systems. The advent of new states of matter will open the way to novel applications in the field of electronics, thermodynamics, sensors, biology [see 1.4.4], health, and medicine.

1.3.2 More is different: the search for new materials

General Overview

The expanse of the periodic system, the sheer infinity of possible molecular assemblies, alloys, and compounds, the very large variety in which a material can take shape (e.g. nano-object, thin film, bulk, crystal, polycrystal, amorphous), and the huge spectrum of methods for materials synthesis and characterization signify that this domain has, in fact, scarcely been touched. It provides an endless source of possibilities and innovation.

Challenges and opportunities

- ✓ Ultra-light, ultra-thin, ultra-strong materials
- ✓ Additive fabrication, relation with mechanics, topological structures
- ✓ Two-dimensional materials
- ✓ Emergent properties from competing quantum states
- ✓ Molecular electronics;
- ✓ Polymer systems
- ✓ Self organization; auto-assembly; self-healing;
- ✓ Materials growth; Clean and sustainable fabrication techniques
- ✓ Alternatives for scarce materials; recycling

- ✓ In-situ and in operando characterization

1.3.3 High temperature superconductors: physics and applications

General overview

Qualified as one of the ten most important open problems in physics, high temperature superconductivity not only stands as a theoretical and experimental challenge, but also as one of the phenomena that holds the most promise for future applications.

The discovery of high-temperature superconductivity (with critical temperatures of up to 56 K) in the pnictide and chalcogenide superconductors in 2006 – 2008 followed that in the cuprates in between 1986 – 1993 (with critical temperatures of up to 135 K). While the mechanisms of superconductivity in these materials remains illusive, the subsequent finding of superconductivity at temperatures as high as 210 K in the H_2S system under very high pressure seems, to everyone's surprise, to follow the predictions of the well-proven Bardeen-Cooper-Schrieffer (BCS) theory for phonon-mediated s-wave pairing. These recent developments indicate that room-temperature superconductivity will be found, be it sooner or later. When it does, it will have a profound impact on all areas of daily life, be it in the energy sector, transportation, health, and medicine.

Challenges and opportunities

- ✓ Development of technological applications
- ✓ Physics of high temperature superconductors

1.3.4 Topological states and novel quantum states

General overview

Effect of topology in mechanics, electronics and physics. Phase transitions without symmetry breaking; topological spin systems; spin liquids; spin ice; role of topological defects; magnetic monopoles; Chiba states; the quantum Hall state; Band inversion; topological insulators, metals, and superconductors; Majorana fermions in condensed matter systems.

Challenges and opportunities

Description of challenges and opportunities in the Horizon 2050

1.3.5 Second Quantum revolution: quantum computing and information

General overview

Aims at the forefront of the second quantum revolution bringing transformative advances to science, industry and society [https://ec.europa.eu/digital-single-market/en/news/european-commission-will-launch-eu1-billion-quantum-technologies-flagship].

Quantum Manipulation of Atoms and Photons [see 1.3.6]

Challenges and opportunities

- ✓ Support growth in scientific activities linked to quantum technologies.
- ✓ Applications, including secure communication networks, sensitive sensors for biomedical imaging and fundamentally new paradigms of computation.

1.3.6 Manipulating photons and atoms: photonics and nanophysics

General overview

Nanophysics: Description of phenomena for materials having one, two or three dimensions reduced to the nanoscale.

- ✓ Historical remarks: e.g. discovery quantum Hall effect in a two-dimensional electron gas, invention of scanning tunneling microscopy, discovery of fullerene as the new form of carbon.
- ✓ Branches of nanoscience and nanotechnology: nano-electronics, nano-optics, carbon nanotubes, magnetic nanoparticles, nano-magnetism and spintronics, quantum transport.
- ✓ Experimental tools of nano-science: e.g. Scanning Tunneling Microscopy (STM), Atomic Force Microscope (AFM), Scanning near field optical microscopy (SNOM), Surface enhanced Raman scattering (SERS), Super-resolution techniques.
- ✓ Nano physics applications: e.g. (nano-electronics, spintronics,...)

Photonics: Science of photon generation, detection, and manipulation through emission, transmission, modulation, signal processing, switching, amplification, and detection/sensing.

- ✓ Historical remarks: e.g. invention of laser, optical fibers.
- ✓ Branches of photonics: Light sources, transmission media, amplifiers, detection, modulation, photonic systems, photonic integrated circuits
- ✓ Photonics applications: laser manufacturing, biological sensing, optical computing, medicine.
- ✓ Attosecond science / UV and XUV generation, nonlinear optics
- ✓ Light matter interaction: Nano-photonics

Challenges and opportunities

- ✓ Materials with engineered optical properties (photonic crystals, metamaterials,…).
  Emerging science and applications of photonics and nanophysics: e.g. quantum information and optics; Information and communication technologies; energy generation and storage.

1.3.7 Extreme light

General overview

- ✓ The interaction of light and matter at extreme energy and power densities; the interaction of light with matter in the relativistic quantum electrodynamic regime;
- ✓ Attosecond science / IR, UV and XUV generation, nonlinear optics

- ✓ Imaging at the attosecond scale: atomic and molecular physics, physical chemistry, reactions, self-organisation of nanoscale constituents, condensed matter physics, biological systems

Challenges and opportunities

Description of challenges and opportunities in the Horizon 2050

1.3.8 Systems with numerous degrees of freedom

General overview

Classical systems with a large amount of degrees of freedom constitutes an enormous area of interest spanning not only physics, but also chemistry, biology, mechanics, social sciences and humanities. In all of these disciplines, the methods developed by physics, be they purely instrumental or the highly sophisticated tools of modern statistical physics, play, and are set to play an enormous role. Among these:

- Physics: non-equilibrium statistical dynamics; crystalline and amorphous systems; glasses; fluid and granular flow; physics of liquids; relation between structure and dynamics;
- Chemistry: nucleation and growth; reactions; rates; catalysis;
- Understanding of turbulence and its implications for energy transfer and its big pay-off in science e.g. from astrophysics, to model how gas flows in galaxy clusters, to climatology, simulating how ocean currents carry heat, and fusion plasmas, simulating the impact of fast particles on turbulence and zonal flows,
- Biology: molecular motors; active matter; non-equilibrium thermodynamics; population dynamics; ecosystems;
- Social Sciences: laws of economics; macro- and micro-economics; the working of markets.
- Humanities: interacting networks [see section 2.3.7]

Challenges and opportunities

Challenges for theory (physics and mathematics) and experiment.

1.4 PHYSICS FOR UNDERSTANDING LIFE

1.4.1. **Searching for life in the universe: What is our place in the universe?**

General overview

The search for answers about life and its origin

- ✓ *What is the meaning of life?* Understanding how life arise on Earth.
- ✓ *Is there life elsewhere in the universe?*
  Search for life in solar planets: e.g. ExoMars / ESA Project with the goal of searching for life in Mars.
  Search for life in extra-solar planets

- ✓ *What comets / asteroids can teach us on the origins of life* e.g. the Rosseta project (ESA)

Challenges and opportunities

Description of challenges and opportunities in the Horizon 2050

1.4.2. **Artificial intelligence: What is the nature of human mind?**

General overview

The accelerating computer power and the advanced software development techniques have set Artificial Intelligence (AI) development in a path of discovery that will forever change the way humans interact with computers and machines in general.

- ✓ From human intelligence to Artificial Intelligence (AI): What is involved in intelligence? What is AI?
- ✓ Goals in AI: engineering approach (to solved real-world problems, build systems that exhibit intelligent behaviour) and scientific approach (to understand what kind of computational mechanisms are needed for modelling intelligent behaviour)
- ✓ AI: Synergy between computer science and engineering, mathematics and physics, psychology and cognitive science
- ✓ The current frontier: recent achievements (e.g. reinforcement learning)

Challenges and opportunities

Description of challenges and opportunities in the Horizon 2050:

- ✓ What makes AI problems hard?
- ✓ Perspectives in engineering and scientific AI goals
- ✓ Paths that may lead to human-level machine intelligence (deep learning)
- ✓ Human benefits and vulnerability

1.4.3 Artificial life: sustainable self-replicating systems

General overview

Progress made for life-like robotics systems, where simple self-assembly, self-replication and complex collective behaviour have been obtained.

Challenges and opportunities

Can we make life in the lab?

1.4.4. **Where physics meets biology: Is there new Physics in living matter?**

General overview

More than half a century ago, physics and biology came together to disentangle the DNA double helix structure, one of the most important discoveries of the 20th century. At present complexity and emergent phenomena are most definitely seen as proper domains where physics [see 1.3.1] meets biology. Emergent phenomena include processes where larger entities exhibit properties that simpler entities do not exhibit and, as a consequence, something new emerges from collective behaviour that could not be predicted by looking at any contributing entity in isolation. This applies to key open question in physics (like superconductivity), but also to key areas in biology like the synchronized behaviour of the human brain or the beating of heart cells.

Challenges and opportunities

- ✓ Physical principles of mechano-chemical networks: new challenges for soft matter physics
- ✓ Systems biology and self-organization: from active matter to cells and tissues
- ✓ Stochastic thermodynamics: from single molecules to complex machinery
- ✓ Physics of biological evolution: from the second law to the selection of structures
- ✓ Perspectives in computational neuroscience studies on brain functions
- ✓ How can simple systems combine to exhibit collective behavior? – e.g. multicellular organisms, neuronal networks / consciousness, population dynamics
- ✓ Coherence effects, complex and active matter, appearance of consciousness

1.4.5. The emergence of life: the Sun-Earth connection

General overview

Life on Earth is sustained by radiative emission from the Sun. This emission varies on all time scales on which it has been observed, by depending on the magnetic features emerged into the solar atmosphere. Current knowledge of the long term changes of solar radiation and of its spectral dependence is uncertain. There is increasing evidence that solar radiative changes have an influence on Earth's climate through different mechanisms [see 2.2.1]. In addition to variable radiative emission, the Sun also emits energetic particles whose flux also changes in time depending on solar magnetic activity. Variations of the solar particle emission cause changes in Earth's atmosphere ionization, global electric circuit, ion-induced nucleation and condensation nuclei in Earth's atmosphere. Understanding climate and life on Earth thus copes with the natural variations of the radiative and particle fluxes received from the Sun. The main science questions are:

- ✓ Origin of life on Earth.
- ✓ How does the solar electromagnetic and particle emission vary at different time scales, from seconds to centuries and millennia?
- ✓ What is the spectral dependence of solar radiative variability?
- ✓ How magnetic field emerged into the solar atmosphere affects the solar radiative and particle emission?
- ✓ How solar variability affects Earth's climate and life?

Description of challenges and opportunities in the Horizon 2050:

While human influence on recent Earth's climate change is clear, and continued emissions of greenhouse gasses in atmosphere will cause further warming and changes in all components of Earth's climate system, improving our knowledge of the solar radiative and particle emission and of the mechanisms behind their changes is fundamental to advance our understanding of Earth's climate system and to improve accuracy of models predicting future climate scenarios.

2. PHYSICS DEVELOPMENTS TO TACKLING MAJOR ISSUES DIRECTLY AFFECTING THE LIVES OF CITIZENS

2.1. PHYSICS FOR HEALTH SCIENCE

2.1.1. Light for health

General overview

History and applications: e.g. laser therapy, surgery, vision correction, endoscopy, health monitoring, bio-sensing

Challenges and opportunities:

Description of challenges and opportunities in the Horizon 2050

2.1.2. Accelerators for health

General overview

Energetic particles, high-energy photons (X-rays and gamma rays), electrons, protons, neutrons and various atomic nuclei species, provide an indispensible tool in improving human health.

The potential of accelerator-reliant therapy and diagnostic techniques has increased considerably over past decades, playing an increasingly important role in identifying and curing otherwise difficult to treat cancers (which is responsible for over a quarter of all deaths in Europe), as well as understanding how major organs such as the brain function and thus the underlying causes of diseases of growing significance to society, such as dementia. One of the most exciting developments in cancer therapy is the use of beams of proton or carbon ions that can reach deep-seated tumors with less harm to surrounding tissue [http://apae.ific.uv.es/apae/].

Challenges and opportunities:

- ✓ Developments in accelerator technology: research into developing more efficient, better performing and more compact machines exploiting new approaches to particle acceleration (e.g. laser plasma acceleration). R&D into improved accelerator designs to provide additional capabilities such as wider range of particles expanding the energy range for different treatment and images techniques
- ✓ Further development of ion (e.g. Carbon and Helium) and Boron-neutron capture therapies
- ✓ Integration of imaging devices for image-guided radiation therapy (including MRI and functional imaging)
- ✓ Integration of measuring devices for dose reconstruction
- ✓ Development of fast and precise simulation and calculation tools in 4D (space and time)
- ✓ Reduction of accelerator cost (e.g. adopting high magnetic field superconductor technology)
- ✓ Improved computer modeling, control and monitoring systems

- ✓ Research & industry collaboration (e.g. EUCARD-2 programme: http://eucard2.web.cern.ch/activities]

2.1.3 **Magnetism for health**

General overview

Diagnosis and therapy of tumors; tissue engineering and reconstruction by magnetic nanoparticles

Challenges and opportunities: Future developments and trends

2.1.4. **High-resolution imaging and medical applications**

General overview

- ✓ History and underlying principles: e.g. Single-photon computed tomography (SPECT), Magnetic resonance imaging (MRI), positron emission tomography (PET), Electron microscopy, super-resolution imaging and bio-imaging.
- ✓ Medical uses and interpretation.

Challenges and opportunities:

- ✓ Further development of computer-controlled treatment methods that enable precise volumes of radiation dose to be delivered and combined 3-D imaging and therapy
- ✓ Availability of increasing accurate, high resolution images, tissue contrast and functional analysis, obtained with imaging techniques such as computed tomography (CT), magnetic resonance imaging (MRI) and positron emission tomography (PET) with the ability to achieve 3D and 4D (that is, over time as well as space) definition: image-guided radiation therapy.
- ✓ Imaging using secondary emissions (e.g. prompt gamma-ray or positron emission) from the proton or ion beam as advanced technique to determine the particle range in a patient.
- ✓ Combined proton therapy and MRI.
- ✓ Treatment using unstable ions such as Carbon-11 to give large PET signal that indicates the location of deposited dose.
- ✓ R&D on the production of novel therapeutic radionuclides and testing alternative production routes of established medical radionuclides.
- ✓ Organic electronics and medical applications.

2.1.5. **Bionic and robotics**

General overview

- ✓ Remote-controlled systems: early beginnings and modern autonomous robots
- ✓ Robots in society
- ✓ Biomaterials (for bionics)

Challenges and opportunities: Future developments and trends e.g. bio-materials

2.1.6 **Artificial tissues, self-repairing systems**

General overview
Review of the existing work in self- healing and self-repairing technologies and issue engineering and applications

Challenges and opportunities

Description of challenges and opportunities in the Horizon 2050

2.1.7 **Plasmas and medicine**

General overview
Direct application of cold atmospheric plasma on or in the human body for therapeutic purposes [e.g. Weltmann and Woedtke PPCF 59 (2017) 014031]

Challenges and opportunities

Further in-depth knowledge of control and adaptation of plasma parameters and plasma geometries is needed to obtain suitable and reliable plasma sources for the different therapeutic indications and to open up new fields of medical application

2.1.8 **Further applications**

- ✓ Lab on a chip
- ✓ Automated diagnostics and analytics

2.2 PHYSICS FOR SUSTAINABLE DEVELOPMENT AND CLEAN ENERGY

2.2.1. **Physics of Earth and the climate**

General overview

Description of physics fields with relevance for the physics of earth, including:

- ✓ The forth interconnected spheres of the earth: Atmosphere, biosphere, hydrosphere and lithosphere
- ✓ Modelling of the Earth System on various spatial and time scales.
- ✓ Modeling of global and regional climate: methods to simulate the interactions of the important drivers of climate, including atmosphere, oceans and land surface
- ✓ The role of solar radiative and particle variability on Earth climate (see section 1.2.3)
- ✓ Earth internal structure

Challenges and opportunities

Description of challenges and opportunities in the Horizon 2050, e.g. Improved measurements for model validation, interactions of aerosols and clouds and effect on climate, regional climate projections.

2.2.2. **Physics fields with relevance for energy technologies: strategies for energy conversion and storage**

General overview

Description of physics fields with relevance for all energy technologies and their impact on climate, including:

- ✓ The energy problem in a world presently dominated by the use of fossil fuels, how do we know their usage has an influence on climate?.

- ✓ Elements of solution by non-fossil energy sources pointing out:

  a) The impact of replacing conventional fossil or nuclear energy sources using intermittent renewable energy sources

  b) The development of massive energy sources, like wind, solar, fission / fusion since the dominance of fossil fuels must decline

  c) The requirements for fossil power plans and technologies to reduce CO_2 emissions and feasibility of large–scale CO_2 storage and/or removal from the atmosphere

  d) Physical capabilities of storing energy systems. What are the energy options and their pros and cons?

  e) Development of more energy efficient systems (household, industry, traffic). Energy efficient electric motors and actuators, including rare earth free permanent magnets based devices

  d) The problems of a circular economy (availability of raw materials), recycling losses and long term sustainability

- ✓ History as a learning strategy, where the issue of energy has a direct impact on economic capacity and social stability.

Challenges and opportunities

Description of challenges and opportunities in the Horizon 2050:

- ✓ Global challenge where the dynamics of energy markets are increasingly due to population growth, increase in economic output and energy demand.
- ✓ Global challenge that would require multi-decade approach, keeping a coherent and sustained energy policy that strengthens the mutually beneficial relationship between education, research and innovation.
- ✓ Global endeavour where new energy strategies require technologies for energy production, storage, conversion, transmission and savings.
- ✓ The quest of fusion energy driven by the need for large-scale low-carbon generation of electricity: large-scale demonstration of fusion energy (ITER) and electricity delivered to the grid through technologies that can be used in the first commercial plants (DEMO).

- ✓ What is the impact of energy on social stability?

2.2.3 **Green Cities: actions on climate change addressing the development of green transport**

General overview

Actions on climate change addressing the development of green transport:

- ✓ New mobility concepts
- ✓ Electric car: research and development to deploy technologies that enhance the performance of electric drive vehicles, including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and all-electric vehicles (EVs). Energy storage technologies, particularly batteries, are critical for the advancement of HEVs, PHEVs, and EVs.
- ✓ New concepts for public transport (automated ground-based and air borne vehicles; connection and synergies between individual mobility and public transport)
- ✓ New concepts for moving people and goods: Vacuum transport (e.g. Swiss Metro or Hyperloop) Magnetic levitation (Maglev) transport.
- ✓ Non fossil powering of long distance air traffic

Challenges and opportunities

- ✓ Mobility of the future
- ✓ Implications of the availability of autonomous vehicles
- ✓ When is the electric car revolution scheduled?

2.3. **PHYSICS FOR SECURE AND EFFICIENT SOCIETIES**

2.3.1. **Environmental safety: air quality, food and water availability, hazardous materials and waste treatment**

General overview

Description of physics fields with relevance for air quality, food and water availability, hazardous materials and waste treatment:

- ✓ **Air pollution** by gases and particles is a major public health issue, with many of its root causes and cures to be found in the energy sector [see IAEA report http://www.worldenergyoutlook.org/airpollution/].
  Energy production and use are the single most important man-made sources of air pollutant emissions.
  Techniques for reducing air pollution.
  Studies of air pollution effects (e.g. on human health, crop yield).

- ✓ **Food and water availability.** Water is key to food security and essential for human well-being and sustainable development.
  [http://www.un.org/waterforlifedecade/food_security.shtml]
  Water pollution due to sewage, industrial processes, and agriculture.
  Depletion of ground water resources.

Technology for treatment of waste water and sewage (including removal of drug residues).

- ✓ **Hazardous materials and waste treatment.** Hazardous wastes and materials are diverse, with compositions and properties that vary significantly between industries and related energy sources. Description of available technologies and their associated cost. Safe storage of Nuclear Waste and transmutation of long-lived nuclides in nuclear waste

Challenges and opportunities

Description of challenges and opportunities in the Horizon 2050:

- ✓ **Air quality:** Avoid pollutant emissions by providing energy services more efficiently or in a way that does not involve fuel combustion. Innovate to reduce pollution costs via technology improvements that will also reduce costs for the post-Paris energy transition. Reduce pollutant emissions to the atmosphere, via stringent emissions limits on combustion plants and vehicles, controls on industrial processes, fuel switching to less polluting fuels and strict regulation of fuel quality. [http://www.worldenergyoutlook.org/airpollution/]
- ✓ **Food and water availability:** Access to safe and clean drinking water and sanitation as a human right. Accelerators and industry: sterilization, water and food treatment and applications regarding biological hazards. Find new ways of agriculture by low water-use farming or water-less farming (e.g. grow plants in sealed greenhouses, supply CO_2 externally) Synthetic production of food components (e.g. sugar and carbohydrates could be produced at much higher efficiency by abiotic processes from solar radiation, H_2O and CO_2).
- ✓ **Waste challenges in nuclear energy**: Technological process: Is it technically feasible to process the wastes in such a way as to produce an immobilised product that is capable of meeting acceptable disposal criteria? Economics and scale of waste management operations: Can waste processing, storage and disposal be carried out on an acceptable scale such that costs are manageable? Public acceptability: Can environmental emissions and geological disposal be managed in such a way as to meet public expectations as well as regulatory requirements?.
- ✓ Establish the links and understanding between climate change and environmental pollution.
- ✓ Can nuclear waste be 'destroyed' by converting long lived (e.g. >100 years) nuclides to shorter lived products?
- ✓ Long-term habitability of Earth as there have been numerous periods in the history of Earth where Earth was not habitable for humans. Can we avoid these periods (e.g. following impact of large asteroids, supervolcano eruptions, nearby supernovae) in the future?.

2.3.2. **Cyber security: networking and grid modelling**

General overview

- ✓ Computer-network developments to facilitate interpersonal communications and access to information.

- ✓ Network topology, technology (e.g. wireless), security (e.g. firewalls, encryption) and protocols (e.g. www).

Challenges and opportunities

Future developments and trends: Human benefits and risks [see 1.4.2.]

2.3.3 **Information and communication technologies**

General overview

Capacity (e.g. magnetic memories) and sensors

Challenges and opportunities,

Future developments and trends: CMOS computing based on magnetic functionalities

2.3.4. **Bio-inspired technologies**

General overview

Initiatives that use remarkable properties of living organisms to solve real world challenges

Challenges and opportunities

- ✓ Neural networks, memories
- ✓ Nanoscale motors
- ✓ Active matter

2.3.5. **Sensors and applications**

General overview

- ✓ Environmental & Earth sensing: e.g. climate change, sensing composition of atmosphere and clouds, forest detection, water quality, natural disaster prevention (e.g. Copernicus programme) https://ec.europa.eu/jrc/en/research-topic/environmental-monitoring
- ✓ Global navigation satellite systems (e.g. Galileo). Space debris and de-orbiting (is it possible to avoid the Kessler syndrom?)
- ✓ Health care sensors (e.g. SQUID and neuronal activity, SERS)
- ✓ Security sensors (e.g. airports and transport control, weapons or threat materials detection, nuclear security)
- ✓ Sensing and BIO-Sensing (spintronic lab-on-chip)
- ✓ Organic electronics
- ✓ Industrial monitoring
- ✓ Physics contributions to the cultural heritage field and strategies for preservation.

Challenges and opportunities

Development of compact and highly efficient systems and the implementation of appropriate data-analysis codes

Improving public understanding and perceptions, through education and communication.

2.3.6. **Understanding and predicting space weather**

General overview

The Sun is the main driver of the so-called “space weather” that causes substantial socio-economic damage on human infrastructures in space and at Earth. This includes both direct effects on specific industry sectors, such as electric power, spacecraft and aviation, and indirect effects on dependent infrastructures and services, such as positioning and navigation systems, electrical power grids, oil and gas pipelines. For example, solar energetic particles ejected in the heliosphere can induce magnetic fields on Earth, which in turn can drive large currents through power networks that can interfere with the network operation, damage transformers and cause power loss. High-energy solar particles can also damage satellites and spacecraft in orbit, with bit swapping in electronics, single-event latch-up (destruction), and solar panels wear. Heat expansion of Earth’s thermosphere during solar storms can also change spacecrafts’ orbits.

As human society becomes ever more dependent on technological infrastructure that fully or partially relies on the space surrounding us, the impact of space weather events becomes increasingly important. For example, the effects of solar storms in Earth's ionosphere can distort radio waves used for communication or corrupt GPS signals, with significant impact on current society. Besides, space weather events can increase the radiation dose at the altitudes of flying aircraft and, in general, the exposition to radiation of in-orbit astronauts. Therefore, in addition to limiting the socio-economic impact of space weather events, their mitigation also implies protection of human life at large.

Over recent years, programmes and infrastructure have been built up by governmental agencies and corporations at national and international levels to predict the solar activity and to forecast its potential impact at Earth and its space vicinity. The main science questions are:

- ✓ What conditions in the magnetic field emerged into the solar atmosphere lead to eruptive events, such as flares and coronal mass ejections?
- ✓ How can we estimate the direction and strength of the particle and radiative fluxes released by these events?
- ✓ How is magnetic flux transported from the solar interior to the heliosphere?
- ✓ Is it possible to fully understand and accurately predict solar magnetic storms?
- ✓ How can human society best mitigate effects of extreme space weather events?

Description of challenges and opportunities in the Horizon 2050:

Space weather describes the way in which the Sun, though emergence of magnetic field into its atmosphere, flares, coronal mass emissions, high-energy particles and subsequently induced space conditions, impacts human activity and technology both in space and on the ground. The goal is to develop robust methods that allow prediction of space weather events with high accuracy, at least 12 hours in advance. This will help mitigate impact on human infrastructure and society, as well as protect human life in flight or in orbit.

2.3.7 **Large-scale complex socio-technical systems and their interactions**

<u>General overview</u>

The physics of very large interacting systems, in which each system node can adapt different states and / or undergo different types of interactions with other nodes: dynamically interacting systems.

Physics can help to develop a "*science able to understand large-scale complex socio-technical systems and their interactions*" and, in particular, to describe the social transitions we are witnessing in present and future times. We refer to the passage towards a fully connected, digital society whose main characteristics and mechanisms we cannot ascertain yet. Internet services are changing the behaviour of the society (Amazon, Airbnb, Uber); people share ideas (Facebook, Twitter), and get informed (Google News, Facebook) or dis-informed (fake news).

A paramount example of large-scale socio-technical structures characterised by interacting networks of data and the perfect laboratory for future research activities are the multiplex and multi-layered network structure of the European urban regions. Almost three quarters of the European citizens will live in a city or urban areas by 2050. Those persons and their local representatives will face global problems such as migration, climate change, and sustainability, with little power of intervention by the local authorities. Diseases will likely start and certainly develop in cities, financial bubbles (e.g. house prices) and fake news production and their diffusion will do. Segregation will start and conflicts will strike in the cities that are then the most efficient places in order to fight inequalities. Urban regions areas will also be the main location to implement the sustainability of development for our society. Statistical physics methods can help to develop scientifically based models of this complexity. Indeed many statistical and nonlinear physicists now work in the area of complex systems, complex networks, multilayer networks and stochastic modelling.

Refining these ideas requires a close cooperation between physicists, social scientists, economists and software developers (i.e. a truly multidisciplinary task). The technological challenge is to unify technologies that are already operational (some at the level of the market) such as local currencies, exchange of goods, pairing of job supply and demand in a single unified framework defined at the level of regional areas that will make possible the collection and redistribution of the data to the users. In terms of data inputs, one needs to focus on technological, ethical and legal frameworks to combine private and public data. In terms of data outputs, one needs to focus on outputs that are relevant for public policy and regulations at the level of a city or given local region bringing a new approach on sustainability and development useful for the entire Europe.

Statistical physics models based on multilayer networks will produce data evidence useful in helping policymakers, groups, and citizens use this evidence to evaluate current policies or regulations (or lack of them), and to propose alternatives (introduce, change, or abolish a policy or regulation).

Challenges and opportunities

- ✓ Create a network platform for the collection, sharing and analysis of a huge amount of suitable data in European Urban Areas.
- ✓ Create a local ecosystem of innovation for the creation of jobs and business for the modern society. Understand the “physics of innovation and creativity”.
- ✓ Shape the future job market that will be created by the new services and opportunities given by the data revolution.
- ✓ Develop reliable statistical physics and complex system models with truly predictive power.

IV. General Guidelines

- **Communicating results for non-experts in the field.** Reports should be prepared for a wide community avoiding (as much as possible) technical jargon.

- **Communicating with Images.** We recommend enhancing the impact of the results by visual communication, as one of the most efficient ways to share information. The authors are encouraged to identify images to illustrate key highlights in the progress reports.

- **The importance of international collaboration.** We encourage underlining the role of international collaborations in main developments.

- **Validation of first-principles theory.** We suggest underlining progress in validation of theories and nature understanding.

- **Industrial applications**. The authors are encouraged to highlight industrial developments and their social impact.

- **Paper extension**: in the range of 10 pages (overview) and 5 pages (challenges and opportunities)