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Applications of nuclear physics to energy: the INFN-E project of the National Institute of Nuclear Physics (INFN)

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Abstract: In this talk, the main issues in radioactive waste management worldwide will be briefly introduced, as well as the world roadmap towards nuclear fusion. Then, an overview of the activities of the INFN-E (INFN Energia) strategic project will be given, showing how INFN's skills on basic theoretical aspects and on the design, construction and use of accelerators and radiation detectors can be applied to specific projects for the characterization and monitoring of radioactive waste as a means to increase nuclear safety and in the context of advanced plants for the study of nuclear fusion.

Keywords: Gamma detectors, Neutron detectors, Radiation monitoring, Nuclear instruments and methods for hot plasma diagnostics

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Contents

1 The rationale for INFN-E project

As a research institution on fundamental nuclear and particle physics, INFN developes several technologies ranging from radiation detectors, to particle and ion accelerators, to electronics. Often, technical solutions developed for nuclear and particle physics experiments can find applications in other fields, notably in medicine, with innovative radiotherapy techniques and non-reactor-based radioisotope production, in the investigation and preservation of cultural heritage, with techniques to ascertain the material content of art and archaeological specimens, in the space field, with specific solutions for satellites and robotic explorers, and finally in the energy field, where technologies can be developed for the characterization, monitoring and surveillance of radioactive waste, for advanced fission systems and for fusion research.

While new technologies in their infancy are typically pursued within the so-called "5th National Scientific Committee" of INFN (CSN5 [1]), INFN-E takes solutions with a higher degree of maturity and supports their further development towards collaborations with outside entities, be them other Italian or international public institutions, European project consortia, private companies. To this end, besides with CSN5, a close relationship is maintained with all INFN offices dealing with external funds (like those coming from the EU Framework Programmes), Technology Transfer and legal aspects. To make a specific example, in the case of muon tomography for the inspection of spent fuel casks (see section 2), our TT office took care of discussing and signing an agreement with the Forschungszentrum Jülich GmbH for a test campaign to be performed at a storage site in Germany.

In the course of the project and depending on the specific target of the activities carried on, collaborations are established with other actors dealing with energy topics, in particular ENEA, RFX Consortium, DTT Consortium, Polytechnic Universities of Milan and Turin, etc.

2 The worlwide situation of radioactive waste and the related issues

The necessity to isolate spent fuel and other radioactive waste from the biosphere makes it necessary to devise solutions for its disposal. Typically, both spent fuel and other types of waste are kept in a so-called interim storage, waiting for appropriate final disposal sites to be available. For radioactive waste with relatively low activity and relatively short decay time, the generally adopted solution is disposal in surface repositories. For waste with higher content of long-lived radionuclides and/or higher radioactivity, depending on lifetime and activity, disposal must take place either in near-surface repositories or in so-called geological repositories deep underground.

According to the IAEA categorization [2], depending on quantity and decay time, nuclear waste is classified into Exempt waste (EW), Very Short Lived Waste (VSLW), Very Low Level Waste (VLLW), Low Level Waste (LLW), Intermediate Level Waste (ILW), and High Level Waste (HLW). To make an example, VLLW typically consists of contaminated protective shoe covers and clothing, wiping rags, mops, filters, reactor water treatment residues, equipments and tools, etc. HLW consists of any matrix that contains a high enough concentration of fission products or actinides (the α-emitting transuranium elements) to require cooling. Examples are spent fuel, waste from the first cycle of fuel reprocessing operations that recover plutonium and unburned uranium, removed highly irradiated reactor components (such as control rods, piping or flow orifices), etc. In countries where no spent fuel reprocessing takes place, spent fuel is a separate category from HLW.

The IAEA estimated that, since the start of the nuclear power era in 1954 to the end of 2013, a total of about 370 000 t HM (tonnes Heavy Metal) of spent fuel was discharged from all nuclear power plants worldwide (excluding India and Pakistan), of which about one third was reprocessed to produce a second round of energy production with recycled fuel [4]. Table 1 reports the volumes of disposed waste worldwide as of 2013.

Table 1. Radioactive waste in disposal, in thousands of m^3, including the volume of packaging [4].

	Solid	Liquid	Total
VLLW	7906	None reported	7906
LLW	20451	39584	60035
ILW	107	8628	8735
HLW	0	68	68

VLLW is suitable for disposal in near surface facilities of the landfill type with limited regulatory control. LLW requires robust isolation and containment for periods of up to a few hundred years and is disposed of in engineered near-surface facilities. ILW requires a greater degree of containment and isolation, which can be provided by disposal at greater depths, of the order of tens of metres to a few hundred metres. For HLW, disposal in deep stable geological formations, usually several hundred metres or more below the surface, is the generally recognized option for disposal. In the case of HLW, the internal heat generated by radioactive decay may have to be taken into account. Near-surface disposal facilities are safely in operation since many years in several countries around the world [3], while the first deep geological repository (for civilian waste) is expected to start operation in Finland in the short term.

International recommendations (e.g. [5]) have guided national policies, strategies and programmes for the management of spent fuel and radioactive waste. Surface or near-surface facilities are a reality in several countries and demonstrated that safe disposal of the corresponding classes of waste can be easily realized. Continuing research on the optimal choices of sites and the prediction of the time evolution of the waste packages underground is performed at international level.

Recently, the IAEA has been promoting an enhanced safety and security culture aimed at improving waste management in its various phases, including "legacy waste" from the past, minimizing direct human intervention (and therefore the possibility of incidents, human errors, criminal actions, etc.) [6]. According to this modern vision, efforts should be made to improve the ability to prevent, identify and intervene on human errors, incidents, thefts, sabotage, unauthorized access, illegal transfers of nuclear material, etc.

Based on the above, one aspect of INFN-E mission is therefore to develop innovative instrumentation to monitor storage and transport of radioactive waste. To this end, specific technologies have been developed, with the goal of producing a "fingerprint" of radioactive waste packages with non-invasive measurements. In particular, neutron and gamma detectors can provide radiological information about the package content. In order to have devices that can be attractive for the nuclear waste sector, simplicity and flexibility of installation, robustness and affordability have been identified as key requirements. Gamma detectors based on scintillating fibers [7] and neutron detectors based on silicon diodes with Lithium deposition [8] have been built with such requirements in mind, and they have been successfully tested at different sites within dedicated European projects [9, 10]. Another technology that can be used for non-invasive inspections of radioactive waste packages is muon tomography [11]. This technique consists in detecting the deviation of cosmic ray muon trajectories when they cross a waste package. By analyzing such deviations, precise images of the content of the package can be obtained. This is useful in the case of legacy waste, whose content information is not available anymore, or for instance to detect possible issues with the content of spent fuel casks.

Another important aspect concerns novel technologies for decommissioning. Within this domain, in INFN-E some R&D has been performed on the possibility to install radiation detectors on drones, or Unmanned Aerial Vehicles, UAV [12]. Regarding instead the possibility to use Unmanned Ground Vehicles, UGV, i.e. robots moving on the ground, compact gamma and neutron detectors have been developed in the framework of CLEANDEM, European project [13, 14].

To decrease the quantity of waste to be sent to geological disposal, it has been proposed to burn at least part of the nuclear waste with Accelerator Driven Systems (ADS), based on a subcritical reactor core [15]. A subcritical core is one where the fission chain reaction does not occur spontaneously in a steady-state, but rather requires an external neutron source to work, such as that produced by an accelerated beam of protons impinging on a thick target. Thanks to the subcriticality, there would be the possibility to mix a certain quantity of Minor Actinides (MA) into the fuel, which would give the possibility to incinerate them by fission. This is called transmutation of the MA into fission products, which can reduce the radio-toxicity of the final materials in the fuel in the long term, such that the confinement time would be reduced by orders of magnitude, from hundreds of thousands of year to a few hundred years. In order to set up such an incineration cycle both partitioning and transmutation are needed. In the partitioning stage, Plutonium and MA are separated from the spent fuel, then in the transmutation stage they are irradiated in a special core to be incinerated [16]. In principle, a true incinerator could be designed in such a way to have a thermal power from the core significantly higher than the beam power, so that it may be possible to convert the fission power to electricity with a net gain with respect to the electrical power consumed to operate the accelerator.

Within INFN-E, studies have been performed about a low-power ADS concept as an experimental and training facility [17]. Such studies have been continued and adapted to the case of hybrid fusion-fission systems [18].

3 The Magnetic Confinement Fusion roadmap

A roadmap towards fusion energy through the ITER [19] experiment and the DEMO [20] plant prototype was established at a meeting of the ITER Council in Saint Paul-lez-Durand, France, on 16 June 2016. Concluding a two year effort by the ITER Organization and the seven Domestic Agencies to establish a new baseline schedule, the ITER Council endorsed the updated Integrated Schedule for the ITER Project, which identifies the date of First Plasma as December 2025. Recently, the roadmap is being revised and a delay of the First Plasma with respect to the previously foreseen date of 2025 is envisaged. In the European strategy, DEMO is the only step between ITER and a commercial fusion power plant. To meet the goal of fusion electricity demonstration by 2050, DEMO construction has to begin in the early 2030s at the latest, to allow the start of operation in the early 2040s.

Among the several technologies that are necessary to make a fusion tokamak work, those that are of interest for INFN are RadioFrequency (RF) and neutral beam plasma heating and some selected diagnostics. An important side activity regards materials. Indeed, in a fusion reactor many infrastructural materials are subject to heavy neutron bombardment resulting in a certain number of dpa (displacements per atom), that result in making metals more fragile. To face this issue, specific projects have been developed whose purpose is to build a powerful neutron source where different materials (e.g. different types of steel) can be tested by exposing them to the neutron flux. This is the goal of the IFMIF project [21], which has been recently expanded by proposing to build the DONES facility in Europe [22]. INFN is heavily involved in both projects, in IFMIF with the prototyping IFMIF-EVEDA stage, where the RadioFrequency Quadrupole (RFQ) component of the deuteron accelerator has been built, installed and is being commissioned at the Rokkasho site in Japan [23], and in DONES with performing R&D on the RFQ design [24].

Recently, the European fusion community approved the Divertor Tokamak Test (DTT [25]), a new project which is part of the research program towards the realization of fusion. The DTT, whose organizational structure was defined in 2019, will be mainly devoted to experiments about the divertor, a specific component in tokamaks which is performing the function of fusion "exhaust", absorbing gas escaping from confinement and contaminants accumulating during operation. In particular, DTT will perform dedicated experiments to study solutions beyond ITER, towards DEMO. INFN is contributing to the development of several components of DTT, i.e. the Neutral Beam Injector (NBI) source [26], the NBI accelerator [27], the RF system [28], the interferometry/polarimetry plasma diagnostics [29], the reflectometry plasma diagnostics [30] and the soft X-ray plasma diagnostics. It is worth emphasizing that in the development of the NBI accelerator as well as the RF transmission systems and launchers, extensive use of the Additive Manufacturing technology is being pursued, specifically studying how to optimize the procedure in order to get the best material characteristics and performances.

As part of the R&D on NBI technology, INFN-E supports a specific activity on the optimization of negative ion sources that are the basis of NBIs. This research is aimed at performing measurements with the small source NIO1, installed in the premises of the RFX Consortium in Padua, Italy [31], and also at providing support to the ongoing commissioning of the prototype source SPIDER, installed in a test lab built on purpose in the CNR Research Area in Padua, near to and under the responsibility of RFX Consortium [32].

Finally, a study carried on with INFN-E support regards the possibility to use polarized fuel as there are indications that fusion cross sections may be enhanced when colliding nuclei are polarized [33]. This can be of interest both for magnetic confinement fusion as well as for inertial fusion (see next section). A challenge addressed by this research is to maintain the polarization of the material during various manipulations, which may require the use of special superconducting magnets based on MgB_2.

4 Inertial Fusion

In this area, INFN recently started the FUSION project, funded by the CSN5, the technology committee [34], and operating in international cooperation with the COST Action 21128 - PROton BOron Nuclear fusion: from energy production to medical applicatiOns (PROBONO) [35]. FUSION aims at carrying out R&D in view of a new class of experiments based on laser systems with very short pulses and high repetition frequency, that have several applications [36]. To this purpose, innovative targets and new dedicated diagnostic systems will be developed [34]. As mentioned in the previous section, the research on polarized nuclei as innovative fusion fuel [33] can also be applied to inertial fusion experiments [37].

5 Conclusions

In summary, with the above examples we see how the cutting-edge technologies developed by the INFN to design and carry out fundamental physics experiments can also serve to provide solutions in the field of nuclear energy, ranging from decommissioning and radioactive waste management, to innovative fission systems, to magnetic confinement and inertial fusion.

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