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The Frascati Neutron Generator: A multipurpose facility for physics and engineering

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Abstract. The Frascati Neutron Generator (FNG) started operations in November 1992 making available to EU fusion community 14 MeV neutrons at an emission rate of 10¹¹ s⁻¹. The fusion community strongly supported the idea of international collaboration in neutronics experiments, data base and code improvement, development of (new) experimental techniques and detectors. FNG was designed and built in ENEA that also operates the machine at its own expenses. FNG is extensively used to perform benchmarks or mock-up experiments of interest to Fusion neutronics in turn validating nuclear data and codes. A number of activities in different fields within a series of collaborations are carried out at FNG so far.

1. The Frascati Neutron Generator facility

The Frascati Neutron Generator is a compact accelerator driven neutron source installed and operating at the ENEA Frascati Research Centre [1]. It relies on both Deuteron-Deuteron (D-D) and Deuteron-Tritium (D-T) fusion reactions, in turn producing almost monochromatic 2.5 MeV and 14 MeV neutrons with a maximum neutron emission rate of 10⁹ s⁻¹ and 10¹¹ s⁻¹, respectively. Figure 1 shows a schematic layout of FNG, where the main components are clearly indicated.



Figure 1: Schematic layout of the FNG assembly. See Ref. [2] for details.

Deuterons are accelerated by means of an electrostatic accelerator up to 300 kV and 1 mA current is delivered onto a Titanium target, loaded with Deuterium or Tritium, where D-D or D-T fusion reactions (namely $D+T \rightarrow n+^4He+17.6$ MeV and $D+D \rightarrow n+^3He+3.27$ MeV) take place.

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In D-T mode, the source neutron emission rate is determined by means of an absolute measurement, the so-called associated alpha particle technique [2]. The D-T reaction produces in the final state a 14.1 MeV neutron and a 3.6 MeV alpha particle, respectively. A calibrated silicon detector, placed inside the drift vacuum tube at 2 m from the target and subtending a small and well defined solid angle to the interaction point, provides the absolute number of the 14.1 MeV neutrons produced at the target by counting the alpha particles from the reaction. Simulations, benchmarked by means of experimental measurements, provide a neutron yield and flux determination within an uncertainty of 3% [1]. In D-D mode the 2.5 MeV neutron emission rate is determined using foil activation technique, where a ¹¹⁵In is irradiated and the gamma activation following the ¹¹⁵In(n,n')¹¹⁵In^m reaction channel is measured by means of an absolutely energy calibrated High-Purity Germanium detector. The D-D neutron emission is measured at $\pm 7\%$ uncertainty. Amongst the D-T compact sources in the world [3], FNG is one of the most intense and this feature, together with its well defined emission rate, make the facility appealing for very accurate measurements. In the following section the main FNG features are presented and discussed as well as a brief overview of the main research and development activities.

1.1. Neutron Spectra, flux and spatial distribution

Figure 2 shows the simulated neutron spectra at different neutron emission angles and the iso-flux contours, as obtained by means of MCNP Monte Carlo code, where an "ad hoc" source routine was implemented. This routine takes in to account all the physical aspects of the neutron production from the beam-target interaction, including ions scattering and fusion cross-section anisotropy. In the MCNP geometry, the target holder and the used detectors dimensions and materials are also described. The Source routine was developed by ENEA Frascati and Institut Jozef Stefan (JSI) in Ljubljana and is available in SINBAD database at NEA.



Figure 2: (*left*) examples of FNG neutron spectra as a function of the neutron emission angle; (*right*) iso-flux contours of FNG.

As it can be noted, the neutron spectrum is almost monochromatic, the neutron energy depending on the neutron emission angle, measured with respect to the deuteron flight direction inside the accelerator tube. Spectrum broadening is angle-dependent as well, being the narrowest at $\theta=90^{\circ}$. The overall broadening of the spectrum a the different angles depend on kinematics, on the deuteron straggling inside the tritiated/deuterated target and on the velocity distribution of the accelerated deuterons. Intensity neutron profiles were measured by means of a Single Crystal Diamond (SCD) detector. Exploiting (most effectively) the inelastic reactions ¹²C(n, α)⁹Be occurring in diamond when neutron energy is beyond the reaction threshold ($E_{th}\sim 5.6$ MeV), it is possible to make spectroscopic measurements at different angles thank to the shift in neutron energy induced by the kinematics of the D-T reactions. Indeed, for 2.5 MeV neutrons the energy is below E_{th} so that intensities profiles are less effective with diamond. The SCD was mounted on a goniometric arm 25 cm in length and fixed on a stepper motor allowing for a fine remote control of the detector position. The SCD signal was preamplified by a ORTEC 142A and supplied with a High Voltage of 300 V by a CAEN high voltage module. Each pulse was recorded by means of a CAEN Digitizer DT5724 and both amplitude and the time of the event (featuring a resolution of 10 ns) were stored in a data file using the "list mode" acquisition. The spectra were registered for 600 s moving the SCD in steps of 5° from the position of θ = -120° to θ = 120°. Left panel in figure 3, shows as a contour plot the evolution of spectra shape as a function of the detector angular position. Is evident the sharpness and the shift toward lower energy of the ${}^{12}C(n,\alpha)^9$ Be peak at high angle. The regions with depressed intensities (namely around $\theta = \pm 90^\circ$) punt in evidence the effect of the materials traversed by the neutron on the detector's line of sight (mostly the metallic target). In the central panel of figure 3, is shown a 3D representation of the pulse height spectra recorded at different detector angular position in the first half of the angular scan. The peak around ADC-chn 4200 is the ${}^{12}C(n, \alpha)^9Be$ reaction signal. It can be noted as moving from $\theta=0^\circ$ to θ =120°, the peak region is higher in intensity and narrower in energy distribution, reflecting the spectrum narrowing already shown in figure 2. In the right panel of figure 3, is shown the integrated counts (sum over the whole ADC scale) projected onto the axis labeling the detector angular position. The two region where the intensity in heavily depressed around $\theta=0$ and 90° are the regions where neutrons intercept the materials of the cooling system around the fusion target. The intensity variation observed between $\theta=0$ and $\theta=120^{\circ}$ (almost symmetric for negative angles) is likely due to detector passing over regions (see contour plot in figure 2) characterized by different neutron fluxes.



Figure 3: (left panel) Contour plot of neutron iso-count rate loci as a function of detector angular position and ADC channel.(central panel) 3D plot representing the distribution of detector count rate as a function of detector angular position and ADC channel; (right panel) Integral count rate obtained by summing over the whole set of ADC channel as a function of the detector angular position.

2. Overview on main FNG research activities performed and future perspectives

FNG can be considered a multipurpose compact neutron source. The activities performed so far include, referring to Fusion related activities:

- 1. Benchmark experiments for ITER: Stainless steel bulk shielding, Nuclear heating, Shut down dose rate, validation of nuclear data libraries and for Advanced Materials [4,5];
- 2. Fast neutron detectors development for the ITER experiment [6-8].

Other activities not related to fusion research

- 3. Electronics: testing and chip irradiation [9];
- 4. Engineering: Characterization of oil extraction tubes;
- 5. Biology: In-vivo mice irradiation to study DNA damaging [10].
- 6. Medicals: Radioisotopes production using 14 MeV neutrons [11];
- 7. Study of moderation systems for 14 MeV monochromatic beams [12]

Future activities are foreseen, such as:

- 8. Further development of fast and thermal neutron detectors without ³He [13-15];
- 9. Production of innovative medical radioisotopes;
- 10. Improvement and upgrade of the source.

As far as radioisotopes production is concerned, it is worth mentioning that an experimental campaign [16] was devoted to the production of ${}^{99}Mo/{}^{99m}Tc$ exploiting the reaction channel ${}^{100}Mo(n,2n){}^{99}Mo$ that exhibits a maximum in the cross section value around 14 MeV. This reaction channel seems exploitable for the intensive production of ${}^{99m}Tc$ radiopharmaceutical, intensively used worldwide for Single Photon Emission Computed Tomography, at present produced in research (aged) fission reactors. This study is important to assess the viability and effectiveness of this alternative route to ${}^{99}Mo/{}^{99m}Tc$ production.

The upgrade project under study for FNG is devoted to increase the neutron emission rate by almost an order of magnitude. This will imply a modification of the ion beam production mechanism that will likely rely on a radiofrequency ion source to obtain a more clean D^+ beam. A new HV station will be used that allow at achieving up to 10 mA D^+ current at a energy around 270 keV. In order to cope with target temperature and power dissipation a rotating target is foreseen following the experience of RTNS-I [17]. This upgrade will allow more rapid and effective irradiation experiment as well as the possibility to amply the possible applications of 14 MeV neutron beams for industrial applications using both 2.5 and 14 MeV enhanced available fluxes. These applications may include for example fast neutron radiography, and tests on radioisotopes such as ⁹⁰Y and ⁶⁴Cu, in alternative way to fission reactors.

Furthermore, following the new moderator concept developed for sealed fast neutron source (HOTNES facility [18]) FNG may produce thermal neutron beams over a large area (in the order of 10^3 cm^2) with high degree of homogeneity for testing of large device of simultaneous irradiation of small sensors. The 2.5 MeV neutron beam available at FNG may be used also as testing beam for moderator development in relation to new and upgrading large scale facilities, while the moderated beam may be useful for development/testing and performance assessment of instrumentation for neutron beam lines operating at reactors and/or accelerator driven neutron sources.

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