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**IRIDE-n**

An **I**nterdisciplinary **R**esearch **I**nfrastructure based on **D**ual **E**lectron linac

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Neutron beams produced by means of photo-production reactions can be applied for:

* **Neutron Resonance Capture Analysis** (**NRCA**): using pulsed epithermal neutrons (roughly below 10 keV down to 1 eV). Several elements in the periodic table show in the absorption cross section intense and relatively narrow peaks (resonances), each resonance being peculiar of the absorbing nuclide. Different isotopes of the same element may have different resonance energy. At a pulsed source the resonance are recognized as peaks in the time of flight spectrum. Each resonance is the fingerprint of a nuclear specie (isotopical recognition) thus allowing for the elemental material analysis (qualitative and quantitative) especially on metallic samples (e.g. cultural heritages). The main requirement for such measurements is the use ot the TOF technique with epithermal neutrons.
* **Bragg Edge Trasmission** (**BET**): This technique exploits the elastic (Bragg) scattering of thermal neutrons. These Bragg edges occur because, for a given *hkl* reflection, the Bragg angle increases as the wavelength increases until 2*è* is equal to 180°. At wavelengths greater than this critical value no scattering by this particular *hkl* lattice spacing can occur, and there is a sharp increase in the transmitted intensity. From Bragg’s law the wavelength at which this occurs is *ë* = 2*dhkl* , giving a measure of the *hkl d*-spacing in the direction of the incoming beam. By means of this technique, stresses and strain in bulky samples can be analysed. This analysis is very important for both industrial as well as cultural heritages applications. This technique is effective using pulsed thermal neutrons and thus the TOF technique is required.
* **Chip irradiation**: when (mostly) a high energy neutron interacts with an electronic chip, the logical state of the latter my change due to the net charge release in the active volume induced by the inelastic n-Si interaction that produce alphas and heavy ions. In complex architecture as Field Programmable Gate Array where complex algorithms can be implemented this interaction may cause the so-called Single Events Upsets (SEU) most of which are transient in nature. SEU were mostly measured usingthe atmospheric neutron field (produced by the primary cosmic radiation in the upper atmosphere) lasting several months of data taking. In order to test the robustness of electronic devices to neutron field in a few minutes, neutron beams produces at facilities are desirable as the may provide an almost atmospheric-like neutron spectrum but several order of magnitude more intense. Also thermal neutrons may be responsible for SEU due to interactions (absorption) of these neutron in the boron present in electronics housing. The major application of chip irradiation are industrial ranging from aviation and aerospace (space programs), to information technologies and radiobiology. In order to perform this kind of studies atmospheric like spectra are desirable at intense fluxes. For this application TOF is not required
* **Radiography and Tomography (NR, NT)**: Neutron Radiography exploits the attenuation of a neutron beam passing through a bulky sample. Each element absorbs neutron depending on its cross section and different isotopes of the same elements have in general different cross section. By means of radiography it is possible tom obtain an image of a object that evidences the internal structure, By rotating the sample with respect to the incident beam and collecting images for each angular position a 3D image of the object is obtained (tomography). These techniques are very important for industrial (automotive and mechanical industry) as well as for cultural heritages applications. This technique is effective with cold and thermal neutrons. For this application TOF is not required.
  1. *Beam requirements and performances*
* **pulsed scenario**: The effective use of **NRCA** described above (having in mind a standard facility like GELINA in Belgium where NRCA was developed) requires electron bunches of 1-10 ns with repetition rate up to about 800 Hz. GELINA operated with 100 MeV electrons at an average current of 100 A with a bunch width of 1 ns and repetition rate of 800 Hz and a rotating uranium target. The width of 1 ns allows GELINA to perform cross section measurements in the so-called non resolved resonance region (hundreds of eV-to-some hundreds of keV neutron energy). Possibly having a 10 ns electron bunch width could be not greatly detrimental for NRCA measurements. In the same current, repetition rate and bunch width of GELINA, we expect to achieve (thanks to the higher electron energy, also using a Tungsten target) a flux higher by a factor of about three. NRCA measurements with the typical fluxes of GELINA last usually about 10-12 hours. Proposing 400 A average current at 1 GeV electron energy, 1(10) ns width and 800 Hz repetition rate we could achieve the same resolution but an order of magnitude higher in the neutron flux, compatible with the more severe cooling requirement due to a much higher power deposited in the target.

The use of the **BET** techniques requires pulsed thermal neutrons at a low repetition rate. A good compromise for the use of these techniques would be 50 Hz repetition rate with 400 A current and 1-10 ns electron bunch width. Considering the 1 GeV electron energy and the current, this configuration would allow to reach almost the same flux of GELINA. The major advantage is that GELINA cannot use the thermal component as the high repetition rate produces a heavy frame overlap for these neutrons. Thus in a configuration with 400 A, 1 (10) ns bunch width, 1 GeV energy and 50 Hz repetition rate we could achieve the same fluxes of GELINA but with the advantage of using effectively also the thermal component of the spectrum.

* **(quasi)continuous scenario**: with the current available in this scenario (quoted in a different document), the neutron fluxes that can be roughly estimated for a tungsten target are about 1013-1014 n/s at the target. In this configuration the techniques using the TOF are not effective (one should envisages the use of choppers to pulse the beam but this heavily reduces the neutron flux at the measuring point). Chip Irradiation, NR and NT can be developed by properly designing the moderator systems.
  1. **Neutron target (Lina)**
     1. **Photo-neutron source by high energy electrons on high Z targets**

Beside reactors, the most powerful neutron sources are accelerators: neutrons can be produced by spallation or by photoproduction. Several studies (ref1) have shown that, when neutron fluxes higher than 1E+16 n/s are required for applications, spallation sources are preferred, while for lower neutron fluxes the photonuclear process will be more convenient in term of investment costs.

Neutrons can be produced by high energy electrons, that interacting in the bulk of the target, loose energy mainly (more than 80%) by bremsstrahlung, producing a photon cascade shower having a continuous energy spectrum, whose end point is equal to the maximum electron energy. These secondary photons can excite the nuclei of the target by one of the following processes (depending on the photon energy, *E*):

* GDR-Giant Dipole Resonance. The electric field of the photon transfers its energy to the whole nucleus by inducing an oscillation (known as giant resonance oscillation), which leads to a relative displacement of tightly bound neutrons and protons inside the nucleus. Absorption of the incident photons excites the nucleus to a higher discrete energy state and the extra energy is emitted in the form of neutrons. For heavy nuclei, the excited nucleus comes into ground state by emission of neutron n (γ,n). Some contribution from double neutron emission (γ,2n) is also possible for higher photon energies. Because of the presence of the large Coulomb barrier, proton emission is strongly suppressed for heavy nuclei (on the contrary, below Z=20 the proton yield is in general larger than the neutron yield).
* QD-Quasi Deuteron Mechanism. When the photon energy is greater than 35 MeV, the cross section for the Giant Resonance neutron production decreases rapidly. For 35 <*E*<140MeV, the photoneutron production is due to Quasi Deuteron effect. In this process, the incident photon interacts with the dipole moment of a neutron-proton pair inside the nucleus rather than with the nucleus as a whole.
* Intranuclear Cascade. Above 140 MeV photoneutrons are produced via photopion production  The neutron photoproduction is a threshold reaction (a nucleon can be delivered from a nucleus only if the energy transferred by the photon overcomes the average binding energy of its nucleons). This energy threshold for heavy nuclei is much lower than for medium or light nuclei: 5 to 7 MeV for the first case and 15 to 20 MeV in the second case.  Moreover, the photoneutron cross sections exhibit a maximum at photon energy between 13-18 MeV for heavy nuclei and 20-23 MeV for light nuclei (A < 40).

It is easily understandable that the choice of the material for the target has been oriented toward heavy elements. In fact, the rate of neutrons produced by photoproduction depends basically on the following two factors: beam power released in the target and atomic number, Z, of the target nuclei

* + 1. **The n@BTF results as reference starting point for the estimation of neutron emission rate for the proposed project**

A pulsed neutron source has been realized at the DAΦNE Beam Test Facility BTF [ref2], [ref3], as a conclusion step of a 3 year feasibility study funded by INFN - CSN5 (Commissione Scientifica Nazionale 5): neutrons are produced in BTF sending high energy (510 MeV) electrons to impinge on an optimized Tungsten target. This kind of source produces neutrons with an energy spectrum that spans over more than 9 decades of energy (from few meV up to hundred of MeV), even if most of them have energy around 1 MeV.

In figure 1 the BTF neutron spectrum, in equilethargic representation, is shown together with the spectra calculated with MCNPX and Fluka in the energy interval, from thermal up to 100 MeV neutrons. The neutron spectrum was measured with a well-established Bonner Sphere Spectrometer equipped with dysprosium activation foils.

The experimental results are well in agreement with the simulations, thus demonstrating the success of the fesibility study of realizing a pulsed neutron source by high energy electron of the DaΦne-BTF.



*Figure 1: Comparison between the simulated and experimental neutron spectra over the whole energy range. (The uncertainty of the experimental fluence <3.1%. MC Statistical errors <4%)*

As predicted for, the majority of produced neutrons belong to the energy range from 10 KeV to 20 MeV and the calculated neutron spectrum has a Maxwellian shape with average around 0.7 MeV.

The experimental and calculated total neutron fluences, collected over a sphere of 10 cm, at the reference point, located 1.49 m apart from the target along the neutron beam extraction line, are reported in the Table 1, confirming again the good agreement between experimental and predicted values

|  |  |  |
| --- | --- | --- |
| Measurements (BSS)  1/cm2/pr | MCNPX  1/cm2/pr | Fluka  1/cm2/pr |
| 8.04E-7 ±3% | 8.06E-74% | 8.12E-7±5% |

*Table1: Total neutron fluence per primary: comparison between experimental measurements and predictions at a well defined reference point around the target.*

The maximum yield of neutron leaving the optimized Tungsten target has been estimated to be 0.212 neutrons per primary (this refers to the DaΦne beam parameter), integrated on all the energy spectrum and all the solid angle. The actual yield of neutrons produced per primary has been estimated to be 0.2189, showing that only about 3% of the produced neutrons are actually absorbed in the optimized BTF W target.

The neutron fluence at the source (just outside the target) has been estimated to be 1.8E-3 n/cm^2/primary, that, for an electron rate of 4.9E+11 e-/s , it corresponds to a neutron flux of about 9.E+8 n/cm^2/s.

Since in the DaΦne -BTF it is allowed to transport a Linac power less than 50 W (for safety reasons), and taking into account the shield configuration and the neutron extraction line, as reported in figure 2, at about 1.49 m from the target, (the reference point for measurements and calculations), the maximum neutron flux is about 4E+5 n/cm2/s: as expected it is mainly composed (≥80%) of neutrons with energy around 0.7 MeV.



*Figure 2: Experimental set-up of the feasibility test of photoneutron production at the Beam test Facility of* DaΦne

* + 1. **Possible Materials for the neutron target**

The Monte Carlo estimations and the experimental results obtained for the n@BTF experiment have been considered as a validated reference from which it is possible derive a preliminary estimations of the neutron yield by photoproduction on the BTF W target (just as it is now), as a function of the primary energy electron impinging on it.

The emission rate will be computed on the base of the electron beam current impinging on the target, assuming correctly that, in the range of energy of interest (up to 1 GeV), almost all the energy of the electrons is deposited inside the target itself (the n@BTF target is a cylinder 6cm thick, about 17 X0).

Obviously since the power of the new superconducting Linac should be at least 3 order orders of magnitude higher than that deliverable to the DaΦne BTF experimental hall, a suitable design of the target must take into account the thermal constrains.

This could lead to some technical choices (segmentation and rotation of the target, use of heavy metal to cool down, etc) that can also affect in a significant way, both quantitatively and qualitatively, the rate and the shape of the photo-produced neutrons.

Anyway, even if the shape, the geometrical dimensions and configuration (that is stationary or rotating one) of the target have to be optimized, taking into account several aspects spanning over multiple fileds (neutronics, thermal heat transfer, activation, metal corrosion etc), the choice of the material is quite well restricted among one of the following materials: Tungsten, Tantalum and Natural Uranium, due to their high photneutron cross sections and high neutron yield.

The photoneutron yield per primary electron is almost the same in case of Tantalum and Tungsten (at 510 MeV is about 8% less in Tantalum respect to Tungsten), while the photoneutron yield is a factor 3 higher for the Uranium, keeping the same target dimensions and primary electron energy), without taking into account the contribution coming from photo-fissions.

Anyway, the case of Uranium at the present has been not furthermore investigated, even if it is well known that could be an interesting solution for the new neutron Facility. It will be certainly included as possible material in the study of the best optimized target for the this project.

The neutron yield [n/s] per unit power [kW] has been already estimated for Tantalum, Tungsten and Lead, using the Monte Carlo code Fluka[ref4]. The predictions have been obtained for electron of 500 MeV on thick targets (i.e, more than 10 radiation length thickness) and have been compared to the corresponding values provided by Swanson’s empirical correlations [ref5], for benchmarking purpose. Swanson operated at SLAC at the end of 1970s, producing an important literature that still today constitutes the main reference for the design guidelines of shields around electron accelerators.

The results reported in the Table 2 show that Tungsten have higher neutron yield respect to the other examined materials.

|  |  |  |
| --- | --- | --- |
| Material | Swanson  [n/kWs]E+12 | Fluka  [n/kWs]E+12 |
| Pb | 1.98 | 2.06 |
| Ta | 2.13 | 2.37 |
| W | 2.42 | 2.67 |

*Table 3: Neutron yield for enough thick targets (>10 X0) and for Ee- = 500 MeV*

Moreover, Tungsten offers several important thermo-mechanical advantages with respect to the other materials, as reported in the Table below:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Properties (T= 300K) | Ta | W | Pb | Unat |
| density(g/cm3) | 16.69 | 19.25 | 10.66 | 19.1 |
| Z | 73 | 74 | 82 | 92 |
| P.M (g/mol) | 180.95 | 183.84 | 207.2 | 238.03 |
| Rad Length [cm] | 0.41 | 0.35 | 0.56 | 0.32 |
| K (thermal-cond)  [W/m K] | 57.5 | 173 | 35.3 | 27.5 |
| E(young) [GPa] | 186 | 411 | 16 | 208 |
| Poisson Ratio | 0.34 | 0.28 | 0.44 | 0.23 |
| alpha μm/m K | 6.3 | 4.5 | 28.9 | 13.9 |
| T(melting point) [k] | 3290 | 3695 | 606 | 1405 |

*Table 4: Thermal and Nuclear properties of several materials*

The main advantages of using Tungsten as the target material comes from the better thermal diffusivity and higher melting temperature respect to the other materials. For this reason, at the state of the art of the project we have mainly focused on this material as possible choice for the new neutron Facility.

* + 1. **Photoneutron Fluence and Spectra as a function of primary electron beam energy**

The yield of secondary neutrons (and other hadrons) that can be obtained by photo production on bulk targets have been estimated by FLUKA code.

The photo-neutron yield, that can be obtained by sending a high energy electron beam on a bulk target, depends mainly on the following factors:

• thickness of the target

 • material of which the target is made

• energy of the primary beam

As described before, the optimized target for a 510 MeV electron beam, as provided by the Linac of the DAΦNE collider (1% energy spread and 1mm mrad) is made of Tungsten and is a cylinder with radius 3.5 cm and thickness 6 cm[ref6]. This target allows to obtain 0.21 n/pr with an energy spectrum spanning over 9 decades, from few eV up to hundred MeV. However more than 80% of the photo-produced neutrons are fast with an average energy of 0.77 MeV (that is the nuclear equilibrium temperature for Tungsten).

The photo-neutron energy spectra that can be obtained from the BTF-like target have been estimated as a function of the energy of the primary electrons interacting trough it, considering 0 divergence, an energy spread less than 0.1% and supposing a circular spot size of the beam on the target of about 2mm diameter. The results are shown in figure 3.



*Figure 3: Neutron Spectra of neutrons emerging from W BTF target (R=35 mm, L=60 mm)*

It can be seen that for the lower energies (up to 100 MeV) the only relevant mechanism of production is the GDR (Giant Dipole Resonance): neutrons are emitted from the nuclei mainly for evaporative process with average energy around 1 MeV. The tail at higher energies is no longer present. The main contribution in the spectra at higher energies comes from the Quasi Deuteron Effect and from the pion decay intranuclear cascade. The bump around 140 MeV is due to the pion re-absorption (the π mass being 139 MeV). The energy spectrum of neutrons photo-produced by 6.7 GeV electrons and positrons, respectively, have been also estimated and, as shown in fig. 2, they match quite well (the two curves overlap in the plot so they cannot be distinguishable). This is due to the fact that the real neutron source are the photons, with energy over the threshold, that are produced by the radiative loss of charged particles in the target: for electron and positron energies greater than the critical one (for Tungsten Ec = 10 MeV) more than 80% of the energy is lost by bremsstrahlung and the rest by ionisation. The energy spectrum of the photons generated in the target in case of electrons and positrons (with the same energy) is almost the same, so that the neutron yield is expected to be the same in the two cases.

The GELINA facility uses electrons of 100 MeV, so that, as shown by the green curve of figure 3 (for 100 MeV primary electron energy), we can assert that in this case the possibility to produce high energy neutrons is strongly suppressed. On the other side, increasing the energy of the primary electrons above 500 MeV, the contribution of the neutrons produced in the upper part of the continuous spectrum becomes no more negligible, even if it is still much lower respect to the one coming from the Giant Dipole Resonance. In particular we have estimated that the percentage of neutrons above 20 MeV is a factor 4 higher for 1 GeV electrons than for 100 MeV electrons.

The Fluka predictions for 1 GeV electrons on the BTF like W target are reported hereafter in the Table 4



*Table 4: Fluka predictions of neutrons escaping from the W BTF-like target per primary electron, integrated over all the solid angle, in case of 1 GeV electron beam*

According the predicted conversion rate “n/e- “at 1 GeV ( 0.68 +/- 0.57 %), a preliminary estimation of the neutron emission rate from a thick W target (DaΦne -BTF like) can be obtained as function of the power deposited:

|  |  |
| --- | --- |
| Power  [kW] | Neutron emission rate  (integrated over the whole energy spectrum and on 4π)  [n/s] |
| 30 | 1.3 E+14 |
| 250 | 1.0 E+15 |
| 400 | 1.7 E+15 |

*Table 5: Preliminary estimation of the maximum neutron emission rate that can be obtained with a W thick target (*DaΦne *BTF likle) with 1 GeV electorns as a function of the energy deposited in the target*

These preliminary estimations allow to figure on that the new neutron Facility we are proposing could reach quite an order of magnitude of emission rate higher than GELINA has.

Anyway it is worthwhile to stress that these predictions assume that all the primary electron energy will be deposited in the target and assume to have a quite monochromatic beam. In the reality, taking into consideration the high density power, a cooling system is required, as briefly described in the following paragraph.

This means that the bulk insulated target, as assumed in the preliminary Monte Carlo simulations, could no more be a real reference case: in fact either the rotation or the segmentation of the target has to be taken into account in addition to the need of using very likely heavy metal to dissipate the thermal power. The presence of a rotating and cooling systems inevitably will reduce the neutron emission rate (because primary electrons do not loose completely their energy in the target and because of neutronic absorbtion form other materials composing the cooling system). However, the correct amount of the reduction of the neutron emission rate will strongly depend on the real configuration of the system and should be accurately determined in dedicated analysis.

* + 1. **The thermal design of the Neutron Target**

A first simplified analytical approach to estimate the maximum temperature that can be reached in a target, assumes to release uniformly the power through the whole cylindrical volume of the W target (R=3.5 cm and H=6 cm). This is a strongly conservative analysis since reduce drastically the density power (that in the reality will depend on the beam spot size as it arrives on the target).

In a simplified stationary assumption the temperature profile is given by the equation [ref7]:



The maximum temperature occurs at the centers (r=0) and is obtained by the following relation:



Assuming to deliver 250 kW uniformly through the volume of the target, with a volume of 170 cm3 (cylinder radius= 3cm and height 6 cm), the power density, q’’’, in the target is q’’’ = 1.5E+9 W m-3. For Tungsten λ = 173 Wm-1 K-1, and supposing to solve a stationary problem with external surface temperature T0= 300 K, Tmax will arrive up to 2500 K. This value can increase by a factor 2 if we consider to deposit the energy with a more realistic beam spot size of 1.5 cm, and in this case, for example, the melting temperature of Tungsten can be exceeded ( T=3700 K).

These considerations put in evidence the possibility of a segmentation of the W target into plates perpendicular to the target axis, that have to be properly investigated. Such a segmentation would create cooling channels in between the plates, through which a cooling liquid can flow. The choice of the coolant has to be done also on the base of neutronic considerations: in principle water can affect more deeply the shape of the target, due to its moderation properties, contrarily to heavy metals, that beside having a lower moderating power, also allow to have much higher cooling power density (resulting for this more effective to save room in between the target slices).

Accurate finite element analysis will be needed in order to properly define the thermal design of the target (transient analysis in multiphysics context), taking into account the real duty cycle and Linac working regime (continuous one or pulsed).

* + 1. **A preliminary estimation of the coast for the neutron Facility**

The Neutron facility has to be equipped by several other important systems and structures, requiring, as well, either a designing or a realization phase, only some of which are listed below:

**-Shielding (for target building, extraction lines, control room)**

**-Extraction lines (thermal, epithermal, fast ones)**

**-Moderator**

**-Shadow bars**

**-Others**

In the following Table we report a preliminary estimation of the costs, keeping in mind that since a complete technical analysis of many aspects is ongoing, this budget could be affect by an error of +/- 30%

|  |  |  |
| --- | --- | --- |
| System sand Apparatus | Sub-structures | Overall costs  (design, development, manufacture and qualification) |
| Shielding | target  extraction line  control hall | 1MEuro |
| Extraction lines and diagnostics | thermal line  epithermal line  fast line | 1 MEuro |
| Target Rotating support and Cooling system |  | 1 MEuro |
| Target +Moderator |  | 500 KEuro |
| Support Activities |  | 500 kEuro |
|  | | TOT 4 MEuro |

* 1. Experimental beam lines (Tonino):

**NRCA** measurements: 20-30 m flight path, moderated beam (e.g. water moderator)

**BET** measurements: with the configuration proposed to use both epithermal and thermal components (50 Hz repetition rate, 400 A, 1(10) ns bunch width, 1 GeV electron energy) the optimized flight path for BET is L < 8 m using a moderated beam.

**NT,NR**: these technique do not use the TOF, so that flight path can be not too long (a few meters). In this case cold/thermal neutrons are needed so that low temperature moderators (e.g. liquid hydrogen, liquid methane) should be used. Neutron guides may be used to transport cold/thermal neutrons so to avoid heavy gamma contamination.

**Chip Irradiation**: desirably a tailored spectrum to resemble the atmospheric one: the flight path should be not too long to maximize flux onto the irradiation area. Spectrum tailoring can be done by a proper choice of modular moderating materials that should be studied.

* 1. Cost analysis
* **Target, cooling, shielding** (larger contribution) (Tina)
  + Description
  + Cost: 5MEuro
* **Lines**: no difference between lines with and without TOF. The cost for a neutron beam line (tubes, shutter, dump, sample tanks) is around 500 kE +/- 20% weakly depending on flight path length.

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