IFMIF-DONES BEAM ON TARGET DIAGNOSTICS BASED ON OPTICAL METHODS: OTR AND FLUORESCENCE*

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Abstract

The IFMIF-DONES facility located at Escúzar in Spain will consist of an accelerator delivering 125 mA of 40 MeV deuterons onto a liquid lithium target. The beam profile at the target will have a rectangular with two side peaks footprint to meet the irradiation requirements of the facility. The environment conditions are characterised by a high radiation background, an atmosphere of lithium vapor, deuteron scattering with the residual gas and secondary electrons production. To measure the footprint under these conditions optical methods are designed based either on measuring Optical Transition Radiation (OTR) of the beam passing through the liquid lithium or on the Beam Induced Fluorescence (BIF) of the residual gas in the proximity of the liquid lithium. Both alternatives have its advantages and drawbacks. In this paper the study of the pros and cons of both alternatives is presented. Furthermore, an experiment to better characterise the OTR response in liquid lithium is also presented.

INTRODUCTION

The objective of IFMIF-DONES [1] is to test materials under a neutron flux of 10^{15} $n \cdot cm^{-2} \cdot s^{-1}$ which generate a damage similar to the ones expected in a fusion reactor. This neutron flux is produced by the reaction of 40 MeV deuterons with liquid lithium at 300 ºC. An accurate measurement of the beam is essential to properly control the material irradiation.

The nominal beam profile at the target simulated in TraceWin is shown in Fig. 1 [2]. It is characterised by a rectangular shape that it can be controlled from 10 to 20 cm as explained in [3]. To measure deviations of this beam profile and send a fast MPS interlock in case of anomalies, an RF pickup based on eight electrodes is under study [4]. However, to have an accurate measurement of the profile for CODAC monitoring, optical methods are considered based on OTR or BIF.

Optical methods are selected because their components and associated electronics can be located far from the target. This is important because the Target Vacuum Chamber Cell (TVC), the beam lithium interaction region, is characterized by a harsh environment of high irradiation [5] and lithium vapour [6]. To minimise these problems, it is proposed to locate the radiation-sensitive components in the Target Interface Room (TIR), guide the image using an image fiber an locate the diagnostic camera and electronics in

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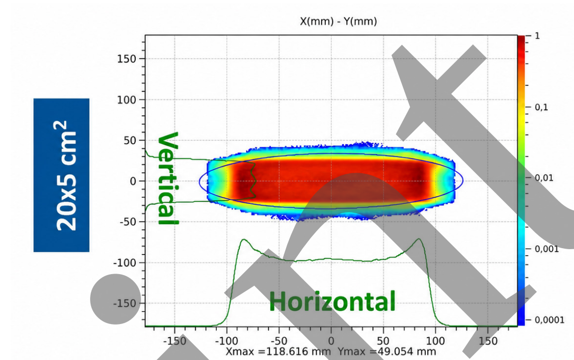

Figure 1: IFMIF-DONES Beam on target profile [2].

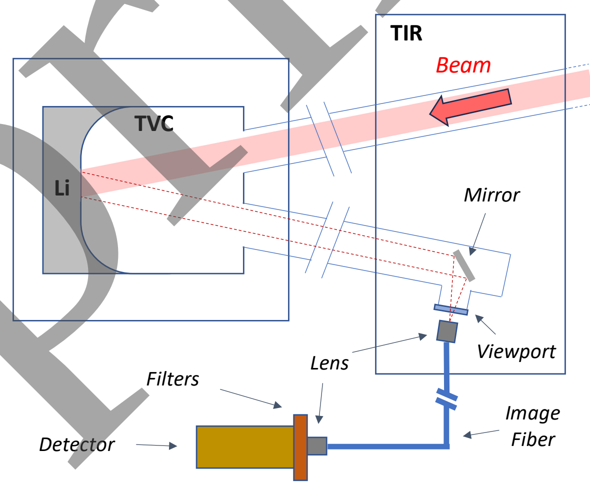

Figure 2: Setup for the Beam on Target diagnostic based on optical methods.

a safe environment, as shown in Fig. 2. Under vacuum, a mirror is used to avoid direct irradiation of optical components such as viewports and lenses. Both, OTR and BIF would share the same setup and the observation of one or another depends on the filters used. The pros and cons of both techniques, based on the light yields and spatial profiles are discussed.

LIGHT YIELDS

The different light yields produced at the TVC have been calculated [7]. The results are shown in Fig. 3. The studied sources are: 1) BIF of deuterons with residual gases, 2) Fluorescence of secondary electrons (SE) with residual gases, 3) OTR of deuterons impinging on the lithium curtain, 4) Thermal radiation and 5) Bremsstrahlung.

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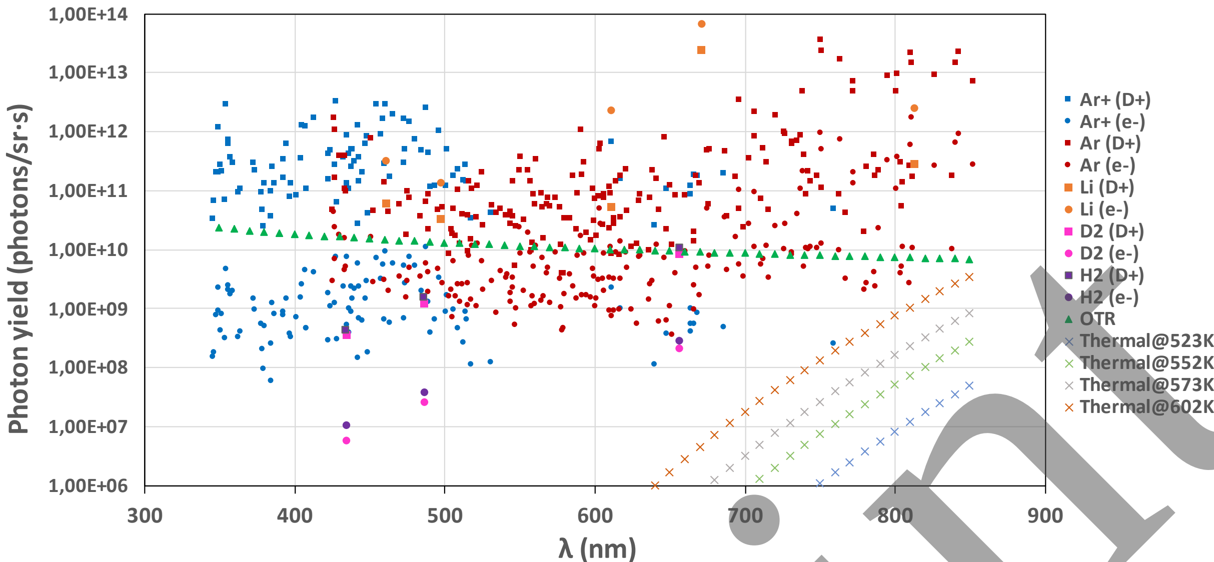

Figure 3: Light sources yields at TVC compared as a function of the wavelength. BIF of argon (neutral Ar and ionized Ar+), lithium (Li), deuterium (D_2) and hydrogen (H_2) due to deuteron beam (D+) and secondary electrons (e-). OTR of deuteron beam impinging on 300 ºC lithium curtain. Thermal radiation of liquid lithium curtain at different temperatures.

The residual gas composition at the TVC is characterised by deuterium (D_2, $3.5\cdot10^{-7}$ mbar) and hydrogen (H_2, $3.5\cdot10^{-7}$ mbar) gases due to desorption form the target, lithium (Li, $1.2\cdot10^{-6}$ mbar) from the outgassing of the curtain and argon (Ar, $1.0\cdot10^{-4}$ mbar) due to external injections [6].

Secondary electrons are produced when the beam ionizes the atoms of the liquid lithium and the residual gas. Electrons yield production coming from lithium ionization is estimated to be 0.017 e-/D+ considering extrapolated data from electron beam irradiation on pure lithium [8]. The electron energy distribution is calculated using the approximation given in [9]. BIF SE cross sections are weighed using this distribution. Electrons produced by ionization of the residual gas have a lower yield based on ionization cross section [10, 11] and are not considered.

The BIF yield, n_{BIF}, is obtained as:

$$n_{BIF} = \frac{1}{4\pi}\frac{I_B}{q}\,\sigma n L \tag{1}$$

, where I_B is the beam current, q the projectile charge, σ the cross section of the BIF process studied, n the particle density of the residual gas and L the length of the path where the interaction takes place. L is estimated with 1.5 m considering the lithium curtain as a concave mirror. The cross section σ data only exists for a given kinetic energy and particle type, thus extrapolations should be made, typically based on the Bethe-Bloch formula [12]. The data used is taken from [13] for Ar, [14] for H_2 and D_2 and [15] for the excitation of Li. BIF is calculated both for the deuteron beam and SE.

The OTR yield per incident D+, n_{OTR}, is [16]:

$$n_{OTR} = \frac{q^2}{4\pi^3\epsilon_0 c}\cdot\beta^2\cos^2(\psi)\cdot|\epsilon_r - 1|^2\cdot C \tag{2}$$

, where q is the deuteron charge, β is the velocity of the beam, ψ the angle of incidence of the beam onto the target, ϵ_r the relative permittivity of the liquid lithium at 300ºC and C a factor depending on the beam velocity, the geometry and the relative permittivity. The OTR yield is a continuous spectrum, but it is grouped in 10 nm bands in Fig. 3. The relative permittivity has been estimated using the Drude´s model [17], since no experimental values of the relative permittivity are found in the bibliography.

Thermal radiation yield of liquid lithium, n_{Th}, is calculated using the Planck´s law [18] with the correction of emissivity [19]. Bremsstrahlung is calculated based on [20] but the yield is several orders of magnitude lower, $n_{Brem}\sim10^{-10}$ ph·str^{-1}·s^{-1}, and it is not shown in Fig. 3. Lastly, radioluminescence is not present at the TVC but in the optical acquisition equipment. Studies are currently ongoing to characterise it.

As shown in Fig. 3, the yield of BIF due to deuteron beam is one or two orders of magnitude higher than OTR. This means that it is difficult to observe exclusively OTR without an overlapping of BIF signal. Furthermore, Ar has several spectral lines in the optical spectrum and very narrow filters (< 5 nm) should be used to isolate OTR from BIF. On the other hand, there is a BIF spectral line of lithium at 670.8 nm which has a high yield and could be useful because the density of lithium is higher in the proximity of the lithium curtain and a more accurate measurement of the beam on target could be obtained. Thermal emission starts to be relevant in the infrared region, but in principle it is not useful as the temperature does not follow the same distribution as the beam profile and the walls thermal emission. BIF due to SE is orders of magnitude lower than from deuterons. Finally, it is noted that these conclusions are based on calculations and assumptions are made. Experiments must be done to better characterise BIF and OTR.

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SPATIAL PROFILES

The spatial shape of the light emitted by OTR and BIF is also studied. OTR is a surface interaction characterised by two lobules form emission [16]. However, only a solid angle of one lobule is seen when placing the detection system far away. As OTR is directly proportional to the beam intensity at the target, and therefore to the beam profile, a direct measurement on the beam shape can be obtained. On the other hand, BIF consist of an indirect measurement, since it is a volume interaction across the beam path through the residual gas.

A simulation to study the spatial profiles taking into consideration the geometry has been done using a 2D ray tracing simulator to trace the photons [21], and a custom python-coded function to generate the light sources. The simulation setup of the horizontal profile is shown in Fig. 4.

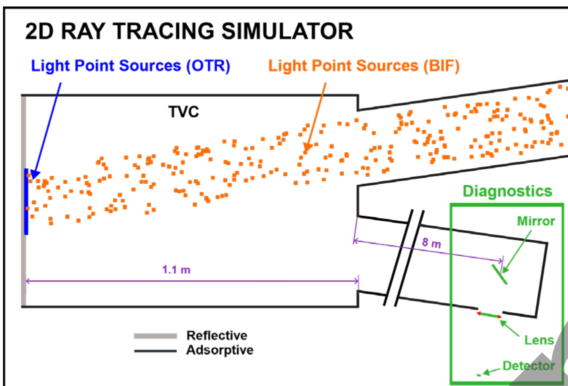

Figure 4: 2D Ray tracing simulation setup.

The simulation consists of the TVC, and the TIR geometry modelled with adsorptive walls except the lithium curtain which is full reflective. The diagnostics based on a mirror, a lens and the spatial detector are simulated. Light points are 360º sources. OTR light points follow beam target distribution as mentioned before. BIF light points are distributed along the beam path uniformly, considering that in horizontal dimension of the transverse beam, the light points follow also the same distribution as the beam profile. The beam transversal dimensions are considered constant though the beam path. No 3D effects are considered. The simulation of the detector response is shown in Fig. 5.

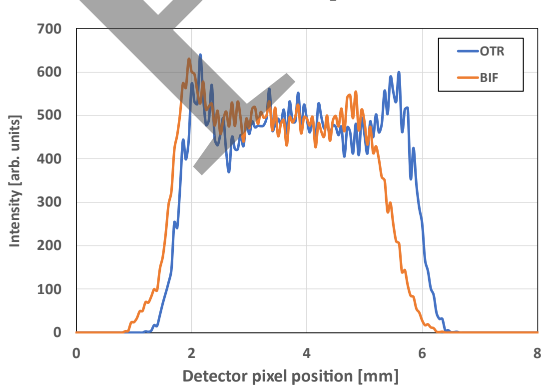

Figure 5: Profiles observed in the detector of the 2D simulation. OTR/BIF ratio is adjusted to compare profiles.

Fig. 5 shows that the OTR distribution is like the beam profile while the BIF distribution is distorted. However, BIF could still be used to have an idea of the beam dimensions. It is remarked that the lithium curtain has been considered as full reflective, and part of the BIF emission is the light emitted in the beam direction and reflected. This may not be entirely accurate due to lithium fluctuations and no mirror reflection and further simulations and experiments are considered for a better characterization.

OTR EXPERIMENT

To obtain experimental yields a setup that measures the OTR from liquid lithium is being built. Special interest is given to deduce the electrical permittivity of 300ºC liquid lithium and reduce its uncertainty. The setup consists of an electron beam of 10.8 KeV continuous 1 mA, which has the same $\beta = 0.203$ and charge per particle as the IFMIF-DONES one of 40 MeV D+. The electron beam impinges on a 300 ºC liquid lithium hold in a crucible heated by an oven. The light emitted is collected in a photon detection system already designed and tested. The OTR yield per incident particle and per solid angle should be the same as in IFMIF-DONES. Figure 6 shows the experimental setup.

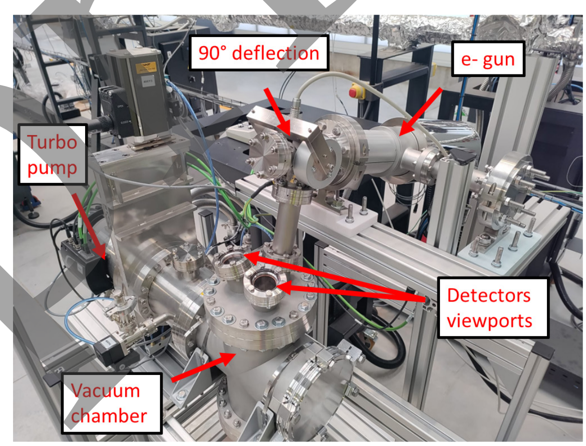

Figure 6: OTR experiment current setup.

CONCLUSIONS

OTR and BIF to measure the beam profile at the target are compared. OTR gives the exact beam profile distribution, but it has a low yield emission. BIF has a larger yield, but the profile obtained is distorted respect to the beam profile. Narrow bands could be used to isolate only OTR emission zones, but the signal noise ratio could be compromised. The 670.8 nm lithium BIF could be the best candidate for the measurement, as the lithium density is higher in the proximity of the target. Both OTR and BIF share the same optical setup. Common challenges are the irradiation damage of optical components, the radioluminescence and the lithium deposition, which are currently under study.

An OTR experiment is presented with the aim of better characterise OTR yield. Experimental work is currently ongoing based on testing the e- gun and measuring OTR on solid targets. The next step will be to adapt the setup to hold liquid lithium as the target for e- beam irradiation.

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