Characterization of proton emission from plasma focus device

4.1 Introduction

Considerable efforts are being made during last few decades to study the interactions induced by protons. Being light ion, proton interactions varies material to materials in view of collisions most likely inelastic arising due to collective states of atom, or due to elastic scattering. During the process electron or nucleon are exchanged, either in successive steps or as clusters, resulting in both energy and intensity being transferred from relative motion into internal degrees of freedoms. The projectile impinges on the target material with enough energy to overcome the work function of the surface so that collision process takes place. Using a variety of detectors and associated electronics we recreate the details of these interactions. The hydrogen serves as particle loading on plasma facing components (PFC) such as tungsten, graphite, beryllium etc, in fusion reactor like ITER. The low energy hydrogen isotopes upon bombardment cause the radiation damage and subsequent accumulation of hydrogen in the component. The micro structural evolution induced by interactions of hydrogen with defects in the plasma-facing components relates with the material degradation and recycling [1]. Also hydrogen recycling is a critical issue for such reactors, which aim to realize the long pulse and steady state operation [2]. The protons have been used extensively to study the interactions on various PFCs of the tokamak reactor. This is why our main aim is to characterize the protons emission from our PF device in order to carry out implantation on materials of tokamak interest.
Due to the exceptional characteristics which are explained in chapter 1, PF as ion source is becoming an interesting research topic for basic physical understanding as well as material processing.

Till now various groups, all over the world studied the general characteristics of protons emitted from different types of PF devices. The energy spectra and space-resolved measurements of fusion reaction protons of the D(d,p)T reaction were studied by Jager et al. [3] in two PF devices (having bank energy of 28 and 280 kJ) by using LR-115A, CR-39, and CR-39/PM-355 covered with Al filters. By putting appropriate Al filters in front of SSNTD detectors, they succeeded to distinguish protons of Ep ≥ 2.5 MeV from deuterons and other fusion products. Moreover, they measured the reaction proton yield of 10^{11} by employing their 2-mm spatial resolution pinhole camera. The ion angular distribution as measured with a set of small SSNTD samples placed upon a semicircular support of 30-cm radius indicated maximum ion flux at an angle of about 20° to z-axis. On the other hand, the ion pinhole camera used by them only registered ion energy above 400 keV because of constraint on the high-pressure zone between the detector and the pinch column. Further, they noticed the track saturation nearly at the center of the ion picture, and the track density of the order of 10^6 at the periphery. The deuteron spectrum as observed by Thomson spectrometer [4] was indicative of two components having energy range of 0.3–0.8 MeV (slow one) and above 0.8 MeV (fast one). Szydlowski et al. [5] reported the measurement of fusion-reaction protons from PF-1000 and TEXTOR tokamak with the help of PM-355-type detectors. In order to find out angular distribution and total fusion proton yield from PF-1000, the detectors were mainly placed inside the discharge chamber at the electrode axis, 90° to it. They observed clear differences in the track numbers as
well as proton energy in both the directions, which may be due to the moving pinch plasma column.

In order to study the proton emission from PF device, we used two types of diagnostics i.e. Faraday cup (FC) and Solid state nuclear track detector (SSNTD). The details of both the diagnostics are elaborately explained in chapter 3. The experimental data of both the diagnostics help us to estimate the parameters like energy spectrum, ion flux and distribution which are very much important for the better applications of this source on material testing perspectives.

4.2 Characterization of proton

4.2.1 Experimental arrangement for FC

As being lighter ion proton can also penetrate the materials of interest upon bombardment through active or passive detector. The one of such process is the FC assembly from where we estimated the ion flux and energy. The use of FC in the present arrangement is being implemented similar to the procedure adopted in chapter 3 in case of neon ion characterization. First of all, we put more emphasis on characterization of proton only at few angles. As mentioned earlier the FCs was placed inside the PF chamber at a distance of 6 cm from the top of the anode and placed them at two different angles (0, 20°). The output of each FC was fed to a digital oscilloscope through an appropriate biasing circuit for monitoring ion beam signal for ion flux and energy respectively. In view of low S/N ratio, we devised a special arrangement for proton as compared to neon ion and found to be effective at axial position rather than at off axis. The only difference is that here we have put two FCs at the heights of 4 and 10 cm from the anode top at the axis of PF device.
This was carried out to remove unwanted scattered secondary electron, which gave added contribution to the signals. We employed a hollow cylinder arrangement to collimate the protons and fixed the two FCs at the two ends of cylinder in axial positions as shown in Fig. 4.1. The optimum chamber pressure for hydrogen filling gas was found to be 0.5 mm of Hg.

4.2.2 Experimental arrangement for SSNTD

In the present work, the ion emission from hydrogen filled PF device was carried out by making the space resolved and time-integrated measurements using CR-39. The schematic of experimental setup is shown in Fig. 4.2 along with the diagnostics. The details of the neon exposed tracks on the CR-39 detectors are described in chapter 3. Samples were cut into sizes of $10 \times 15 \text{ mm}^2$ and placed inside a drift tube at a height of 6 cm from the top of the anode. CR-39
detector was placed inside a drift tube at a high vacuum of the order of $7.5 \times 10^{-5}$ mm of Hg by making use of a diffusion pump, whereas pressure inside the PF chamber was maintained at 0.3 mm of Hg by employing a rotary pump. A 0.5-mm diameter pinhole was used as the entrance of drift tube, which not only collimated the proton beam but also enabled differential vacuum to be maintained between the drift tube and the PF chamber. The entrance pinhole of the drift tube was kept at a height of 3 cm from the top of the anode so that emitted ions of the plasma column suffered minimal attenuation in the background gas medium. After irradiation by the collimated proton beam, the tracks left in the CR-39 material. The detail of the etching process and visualization of the tracks are discussed in section 3.2.3 of chapter 3.

Fig. 4.2: Experimental setup for SSNTD studies
4.3 Results and discussion

4.3.1 FC analyses

First of all, we have fixed two FCs at angular positions of 0 and 20° inside the vacuum chamber to record the signal of protons. The typical signals of the FCs obtained at 0 and 20° is illustrated in Fig. 4.3 (a,b). The distributions of density of protons as a function of energy at two above mentioned angles respectively are shown in Fig. 4.4 (a) and (b). From the plots it is observed that low energy protons have more density than that of high energy. For example, the most probable energy value lies from 10 to 20 keV and the maximum energy is up to 1 MeV at 0° and in that case the maximum proton density found to be approximately $0.8 \times 10^{20}/m^3$ which

![Fig. 4.3: Typical FC signals at positions of (a) 0° and (b) 20°](image-url)
Fig. 4.4: Proton density vs proton energy at (a) 0° and at (b) 20°

is evident from the Fig. 4.4 (a). Similarly, the most probable energy value lies from 20 to 30 keV and the maximum energy is 1 MeV at 20°, also evident from Fig. 4.4 (b). In that case the maximum proton density is the order of $1.1 \times 10^{20}/m^3$.

As an improvement of the above technique, the two FCs are kept at the 4 and 10 cm respectively inside a hollow cylinder from the anode top and signals were recorded and it is
shown with the \( \text{d}l/\text{d}t \) signal in Fig. 4.5. Measuring the time delay between one point of the FC1 ion signal and the equivalent point of the FC2 ion signal, we estimated the proton ion energies \( (=1/2m_p v^2) \). For instance, the delay time between two FC signals is 0.05 \( \mu \text{s} \) in one case, which are 1.33 and 1.28 \( \mu \text{s} \) at the height of FCs at 10 and 4 cm respectively. By this technique the highest energy of protons is obtained to be approximately 1.2 MeV. As explained in equation (3.4) in chapter 3, we have seen that density of proton, \( n_i \) is inversely proportional to \( v \).

![Fig. 4.5: Typical signals of two FCs along with \( \text{d}l/\text{d}t \) signal](image)

Therefore, the \( n_i \) and \( E \) (energy of the proton) always obey a relation. During the linear fitting with all the experimental points, i.e, \( y=mx+C \); we have obtained the slope, \( m=-0.81785 \) and the constant, \( C=20.5611 \) which is shown by the continuous curve in Fig. 4.6. From the experimental data we arrived at a generalized power law of the following form:
And the distribution of proton density vs energy at the axial position of FCs is illustrated in Fig. 4.6. Similar kind of power law of the number density distribution as a function of energy has been discussed in case of nitrogen ion by Kelly et al. [6]. They carried out the best fitting of the spectrum which corresponds to two spectral laws depending upon ion energy regime. The estimated highest energy of proton in our work is found to be around 1.2 MeV with a density of $10^{20}/m^3$.

4.3.2 SSNTD analyses

Once the protons are exposed on SSNTD samples in our PF device by varying the number of shots, then tracks are formed. In order to reveal those tracks we have employed etching method, and then observed by using OM as mentioned in chapter 3. After acquiring the picture of the tracks, we randomly selected three different areas (each of 8450.07 μm²) from it. From these three selected areas, the track numbers and diameter were calculated manually and the average value with standard error was estimated. The calculated track numbers per unit area furnish the track number density.
The explanations of the track formation, etching process and energy loss of the ion are discussed in section 3.5.1 in the chapter 3. Protons are very light ions (Z=1) and so their energy loss in any detector medium is comparatively low than that of heavy ions (for Ne, Z=10). Therefore, the energy loss as well as range by virtue of Bethe formula is small but provides a significant contribution. That is why their calculations demand to be much more accurate. The stopping power and range of the proton in CR-39 which are calculated using SRIM code [7] analyses are shown in Fig. 4.7 and 4.8 respectively. First of all, to verify the effect of electromagnetic radiation on track formation in the CR-39, we kept the detectors having size of

10 x 15 mm² on the top as well as at the side of the chamber, and these detectors were exposed to few PF shots at nonpinching mode of operation, i.e., at higher filling gas pressure. After etching these exposed detectors, we did not find any impression of track on them and thereby confirm that the electromagnetic radiation has no significant effect on CR-39 detectors. Thus, one can safely use such detectors in harsh electromagnetic environments [3]. Next, we have
characterized the axially moving proton beam by placing bare CR-39 detectors (without covering the detector by ion filters) at a height of 6 cm from the top of the anode without using the drift tube arrangement. After exposure to PF shots, the etched detectors appear milky white to the naked eye. While viewing under optical microscope, the detector shows the stack of tracks uniformly distributed all around the surface, as shown in Fig. 4.9. The micrograph indicates that the detectors might have saturated due to high fluence of proton beam [8]. Further, we suspect the role of the scattered proton in the saturation of detectors. Therefore, in order to obstruct the scatter proton from reaching the detectors, we placed the detectors inside the drift tube (as shown in Fig. 4.2) and thus allowed a well-collimated proton beam to fall on the detector surface. However, after etching, the detectors were still found to be saturated. The systematic study carried out by Gaillard et al. [8] on saturation of CR-39 detectors reveals that the particle fluences above $10^8$ particles/cm$^2$ turn the detector into a saturation regime so that direct track counting is not possible. Thus, as it well known that the particle density of pinch plasma is around 10 orders [9] more than that of the saturation limit of CR-39 detector, one can expect the turning of non-opaque detector to milky white due to overexposure, i.e. high fluence of particles. There are quite a few papers on saturation effect in SSNTD due to high fluence of ions. As far as our knowledge is concerned, as of now only Castillo et al. [10] have reported the saturation effect on track detector while detecting the axially moving fusion protons (3.03 MeV). However, they have not reported any way out for overcoming the saturation effect of SSNTD due to high fluence ion emission from the PF device.

We have used a simple technique to overcome the saturation or overlapping effect of CR-39 detectors by covering them with ion filters. Figs. 4.10 (a)–(c) illustrate the typical micrographs of proton tracks of detectors covered with Al filters of 2, 4, and 6 µm. The
micrograph shown in Fig. 4.10 (a) clearly depicts the formation of proton tracks with different diameters, which are uniformly distributed on the surface of the detector. Individual and well-separated tracks are mostly seen in the micrograph along with a few overlapped tracks. Protons of above 220 keV can pass through a 2-μm Al filter [7] and hence the tracks formed in Fig. 4.10 (a) must be due to the protons of above 220 keV. The dimensions of tracks depend upon the proton energy as well as etching time [11] and hence different diameters of tracks are suggestive of the emission of polyenergetic protons from the PF device. Nearly circular tracks in the micrographs indicate that the axially emitted protons of PF strike the detector in normal incidence and the tracks induced due to scattered protons might be overruled. The lower limit of proton energy estimation is limited due to the saturation effect of track detector and threshold energy for creation of tracks in CR-39. However, by increasing ion filtration foil thickness, one can easily approximate the upper limit of proton energy estimation. Hence, we have attempted to get a rough estimation of maximum proton energy by putting 4–10 μm Al filter in front of the

Fig. 4.9: CR-39 exposed to proton in the background
detector. The micrographs of tracks shown in Figs 4.10 (b) and (c) are still indicative of sufficient number of impressions of proton tracks and the micrograph obtained by covering the detector with 10-μm Al filter (not shown in figure) confirm the emission of proton energy of MeV range. High energy protons can pass through the material and can make the tracks of small diameter because of small interaction time and small specific energy loss (as \(\frac{dE}{dx} \propto 1/E^2\)) in terms of energy straggling. On the other hand, low-energy protons follow \(\frac{dE}{dx} \propto \frac{M Z^2}{E}\), where \(E\) is the incident energy, thus low-energy track sizes were observed [12]. Track density as a function of track diameter at various etching hours has been studied and results are shown in Fig. 4.11.

Fig. 4.10: Micrograph of proton track covered with (a) 2μm, (b) 4μm and (c) 6μm Al filters
Fig. 4.11: Track density as a function of proton track diameters with (a) 2 \( \mu \)m (b) 4 \( \mu \)m and (c) 6 \( \mu \)m Al-filters

When we increase etching hours in case of different thicknesses of Al filters, the most probable track diameter has shifted from 2.5 to 4.5 \( \mu \)m, 3.5 to 6.5 \( \mu \)m, and 1.5 to 5 \( \mu \)m in case of 2, 4, and 6 \( \mu \)m Al filters, respectively. This can be explained by the fact that the tracks are
etched out to the largest diameter only when the etchant solution enters the end part of the pit without restraint. The etchant has unconstrained access to the end part of the particle trajectory only after removing the external layer of the detector during the etching process. If we increase the etching hours, the etchant material will remove the external layer deeper, resulting in more damaged material area, and as a result the size of the track diameter will be increased. A very interesting feature of all these detection characteristics, i.e., track diameter versus etching time,

![Graph showing reduced ion density after passing through various thicknesses of Al-filters]

Fig. 4.12: Reduced ion density after passing through various thicknesses of Al-filters

can be explained by detected particle atomic number and its energy to mass ratios [13]. After all, this phenomenon is related with the energy loss of the particle on the material or samples and it follows from the fact that dE/dx value of any particle, as well as its restricted energy loss (REL), is maximum at the end of the range [13]. Similar results were also observed by Malinowski et
al. [14]. As the proton fluence reduced by using various thicknesses of Al filters, the track number density decreased. This is because, depending on the thickness of the degrader the class of particles exhibiting low energy is not allowed to pass through the medium. On the other hand, the remaining high-energy particles easily pass through the filters and strike the detector. Fig. 4.12 illustrates the track density as a function of thickness of Al foils (μm) for various etching hours, and it is found to be linearly decreasing in nature. The track diameter evolutions, expressed as a function of etching time, have been presented in Fig. 4.13. These results are in good agreement with some of the previously reported results [13, 15]. These diameters still increase linearly for 4–8 h, although a critical detector layer (equal to the ion range) was removed earlier [16]. Moreover, while carefully analyzing the graph of Fig. 4.13, one can notice two distinct linear structures, one having between 2 and 4 h and the other being from 4 to 6 h. Higher as well as low-energy protons are contributing to the lower part (from 2 to 4 h) of the graph, whereas only high-energy protons are responsible for the rest part of the graph (above 4 h). A difference in the slope of the two parts can be easily marked from the graph. Our observation of lower slope in case of upper part (above 4 h) is in agreement with the results reported by Szydlowski et al. [13]. They have observed that track diameters rise slower as a function of etching time for high energy proton.
4.4 Conclusion

In conclusion, the estimated highest energy of proton using FC technique in our device is found to be \(~1.2\) MeV with a density of \(\sim10^{20}\) m\(^{-3}\). In view of low S/N ratio, proton signals can be improved with special care and proper groundings. Also, the space-resolved and time-integrated characteristics of the proton beam emission from the PF device have been studied by employing CR-39 detectors. The characterizations of protons have been done mainly at axial position and have been extracted into the drift tube from the very neighborhood of the pinch column. To remove the saturation effect on the CR-39 detector because of intense proton fluence, the idea of using Al filters in front of the detector has been conceived specifically for our experiment and is well-suited to remove the saturation effect by reducing the fluence of protons. A strong correlation between the dependence of the track density and sizes and the thickness of Al filter and etching hours has been noticed. Finally, CR-39 detector has some threshold value while FC has the advantage over detection of whole range of energy of protons.
References