Gas Electron Multiplier foil holes: a study of mechanical and deformation effects

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L. Benussi,[a] **S. Bianco,**[a] **G. Saviano,**[a,b] **S. Muhammad,**[a,b,c,1] **D. Piccolo,**[a] **A. Suhaj,**[d]
A. Sharma,[f] **M. Caponero,**[a,e] **L. Passamonti,**[a] **D. Pierluigi,**[a] **A. Russo,**[a] **A. Lalli,**[b] **M. Valente,**[b]
M. Ferrini,[b] **S.A.E. Langeslag,**[f] **S. Sgobba,**[f] **I. Aviles,**[f] **A. Magnani**[g] **and I. Vai**[g]

[a]*INFN, Laboratori Nazionali di Frascati,*
Via Enrico Fermi, 40, 00044, Frascati, Rome, Italy

[b]*Department of Chemical Engineering Materials & Environment, University of Rome, "La Sapienza",*
Via Eudossiana, 18 00184, Rome, Italy

[c]*National Center for Physics, Quaid-i-Azam University Campus,*
Shahdra Valley Road, Islamabad, Pakistan

[d]*Department of Physics and Astronomy, University College London,*
Gower Street, London, United Kingdom

[e]*Centro Ricerche ENEA Frascati,*
via E. Fermi 45, 00044 Frascati, Rome, Italy

[f]*CERN, European Organization for Nuclear Research,*
385 Route de Meyrin, Geneva, Switzerland

[g]*INFN Section at Pavia and Department of Physics, University of Pavia,*
Via Bassi, 6 - 27100, Pavia, Italy

E-mail: Saleh.Muhammad@cern.ch

Abstract: The GEM detectors will be installed at the Compact Muon Solenoid (CMS) experiment during Long Shutdown II of the LHC in 2018. The GEM foil is a basic part of the detector which consists of a composite material, i.e. polyimide coated with copper and perforated with a high density of micro holes. In this paper the results of the GEM foil material characterization are reported, and a campaign of tensile and holes deformation tests is performed. During the tests, the complex radiation environment at CMS is taken into account and samples are prepared accordingly to see the impacts of the radiation on the GEM foil, i.e. non-irradiated samples are used as the reference and compared with neutrons- and gamma- irradiated. These studies provide the information necessary to optimize the stress level without damaging the foil and holes during the detector assembly in which the GEM foils stack is stretched simultaneously to maintain the uniform gap among the foils in order to get the designed performance of the detector. Finally, an estimate of the Young's modulus of the GEM foil is provided by using the tensile test data.

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[1]Corresponding author.

Contents

1 Introduction to the GEM (GE1/1) detector project for CMS

The CMS is one of the two large multi-purpose experiments in the Large Hadron Collider (LHC) at CERN having the goal to investigate a wide range of physics such as Higgs decay channels, dark matter and super symmetry searches. During the second Long Shutdown (LS2) of the LHC, which is planned to start in 2018, an upgrade to the collider will be undertaken by increasing the instantaneous luminosity up to $2 \times 10^{34} \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$ [1].

Originally, the CMS muon subdetectors system was designed with three different detection technologies. Drift Tubes in the barrel provide precision measurements and level 1 triggering (covering up to pseudorapidity $|\eta| < 1.2$), Cathode Strip Chambers in the endcaps covering $1.0 < |\eta| < 2.4$ [2], and additional Resistive Plate Chambers which provide redundant trigger and coarse position measurement in the barrel and the endcap. Previous studies [3] have shown that an acceptable trigger rate for muon with $P_T < 25 \, \mathrm{GeV}$ is not possible without efficiency losses in the endcap region of the CMS, which represents over half of the CMS muon coverage. Therefore, the CMS muon system must be improved to maintain the high level of performance achieved in Run 1 in the environment of the high-luminosity LHC (HL-LHC).

The installation of an additional set of muon detectors called GE1/1 by using GEM technology in the first endcap muon station will be a relevant improvement in the CMS muon system with respect to many aspects. The GEM detector will maintain and even improve the forward muon triggering in the $1.6 < |\eta| < 2.2$ [4] region, since at higher luminosity of the LHC the trigger rate will be large and difficult to control in this region due to higher background rates and lower magnetic field strength. The GEM detectors need to be highly resistant to radiation as they will be exposed with high doses of radiation (neutrons flux $\approx 10^5 \, \mathrm{Hz/cm^2}$ [5]) due to being located closest to the collision point in the endcap. The studies show [6] that due to neutrons the discharge probability of the GEM detector is negligible, therefore this detector can perform efficiently in the intense neutrons environment.
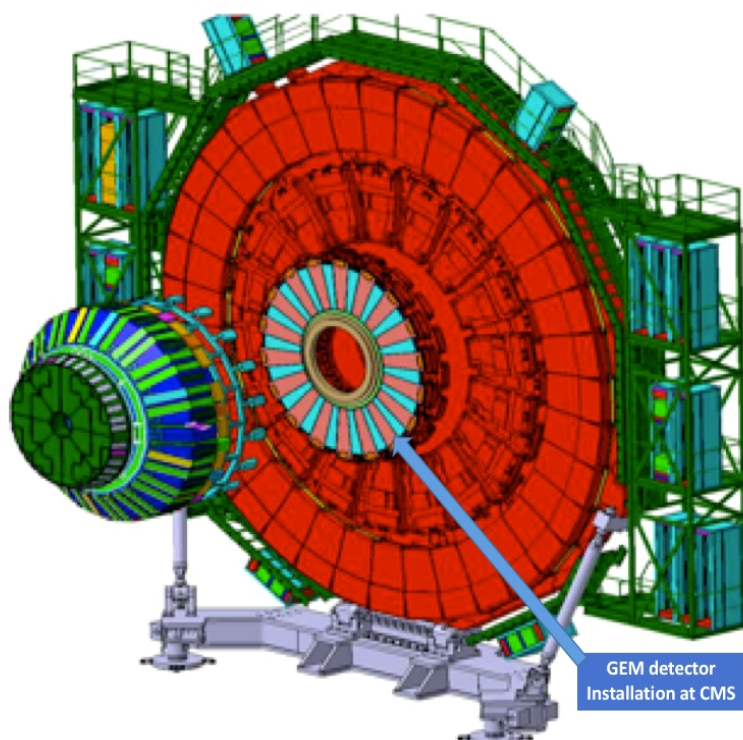
Figure 1. GE1/1 installation location at CMS [5] first endcap station.

2 GEM detector assembly procedure

A GEM chamber consists of a stack of three GEM foils that are sandwiched at their edges between four layers of thin halogen-free glass epoxy frame. An additional Printed Circuit Board (PCB) board, serving as the drift board, is located at the bottom of the stack with another (readout) board on the top. The entire GEM stack is contained within a large outer glass-epoxy frame manufactured from a single piece which provides the border of the gas volume. On both sides of the outer frame a groove is machined, running around the entire frame into which Viton O-rings are inserted.

The drift board is prepared by equipping the PCB with metallic inserts and high voltage probes that are fixed to the outer frame using guiding pins. To assemble the GEM stack, the first layer of the epoxy inner frame is placed on rigid support on top of the drift board. The first GEM foil and the second layer are then placed on top. Stretching nuts attached in small brass posts (the "pull-outs") are then inserted into the inner frame, and located every few centimeters in the inner frame. When they are tightened, the GEM foils become tensioned as the inner frame is pulled outwards. The other two GEM foils and layers are then placed on top of each other to close the stack. To keep the stack closed, holes in the frame and in the foils are located at every centimeter, and stainless steel screws are inserted into them and tightened. The spacing between the individual GEM foil and drift/readout board is as follows: drift gap/ GEM1-GEM2 transfer gap/ GEM2-GEM3 transfer gap/ induction gap: 3/1/2/1 mm [5].

The guiding pins are then removed, the whole stack is placed on the drift board and the readout PCB is placed on top of the outer frame to close the chamber. The drift and readout PCB are

attached to the brass pull-outs with a series of stainless steel screws. This sandwiches the outer board between the drift and readout board, effectively creating a solid gas barrier apart from the gas inlet and outlet located in diagonally opposite corners of the outer frame.

The GEM foils stack is tensioned by pulling the stack outwards against the brass pull-outs, which is done by manually tightening the screws going through the pull-outs and the inner frame. The operational procedure indicates a torque of about 0.1 Nm as necessary and sufficient to provide uniform stretching [5]. Dedicated tests showed that the force applied by each screw on the foil is 10 N. Each screw is located 1 cm apart from the nearest screw. Such a force corresponds to 16.7 MPa.

3 The GEM foil material, stretching and radiation effects

The GEM foil consists of polyimide (Kapton) [7], copper coated on both sides and perforated with a high density of holes [8]. The Kapton foil is 50 μm thin and the copper coating is 5 μm on each side. To manufacture Kapton, a polyimide chain is built up from a large number of chemical repeated units [9]. Copper and Kapton are both ductile materials separately; however, the perforation of the GEM foil causes it to acquire a brittle-like behavior, instead of purely ductile. During assembly the GEM foils stack (three foils) is stretched, the polymer molecules change their shape, i.e. elongation occurs in all directions if the stretching force is uniformly applied.

The assembly technique devised for the GEM detector allows for positioning and re-positioning of the GEM stack multiple times, in order to cope with repairs such as replacement of a single GEM foil. In the case of several stretching and loosening cycles, the GEM stack can be subject to repeated stress cycles. The characterization of tensile properties of the GEM foils is therefore very important, in particular the stress-strain relationship (figure 3) provides a clear determination of the elastic limit which should not be exceed in order not to produce deformation of the holes.

Another important aspect that has to be taken into account is the radiation degradation of the GEM foil. The radiation degradation mechanism in the polymer is an exceedingly complex phenomenon and constitutes of numerous chemical reactions sequences that result in changes of the molecular structure. Significant changes in material morphology can also occur [10, 11]. In the case of the GEM foil, as polyimide is coated with copper, the radiation degradation phenomena become more complex. Up to date, no information is available on the mechanical degradation of GEM materials, which in general will depend on energy, intensity and type of the incident ionizing radiation.

A series of tensile tests were therefore performed to observe and characterize the possible effects of radiation (neutrons and gamma) on the GEM foil material. From this study we can estimate the stress and strain range in which the holes started to deform and in this way we can determine the safe stress range for GEM detector assembly.

4 Samples description, experimental setup and testing procedure

To test the tensile properties of the GEM foil and hole deformation under continuing increasing stress till rupture, three sets of the samples were used. Non-irradiated samples were used for a reference. Neutron-irradiated samples were exposed in the Louvain neutron facility in Belgium. The neutrons dose absorbed by the samples was approximately equivalent to 10–12 years run at CMS, which is 20 Mrad (0.2 MGy) and 10^{14} n/cm^2 [12] at defined LHC luminosity. The third set
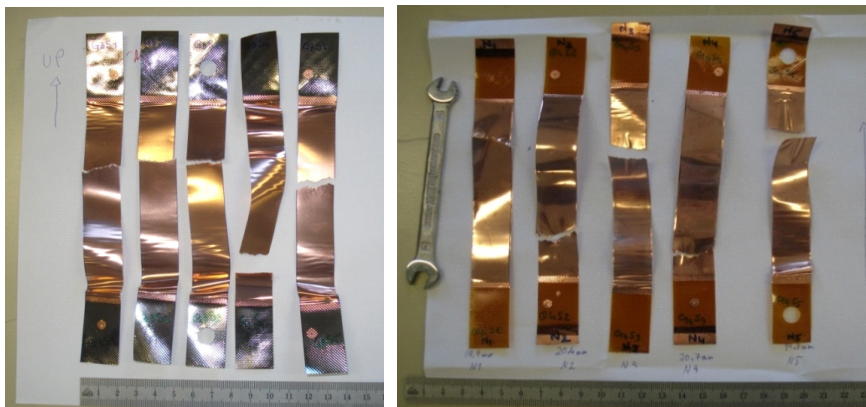
Figure 2. (Left) set of the non-irradiated samples. (Right) set of the neutrons irradiated samples after the tensile test completion. A ruler is used for a scale.

of samples was irradiated with gamma rays in CERN Gamma Irradiation Facility (GIF) [13] where ^{137}Cs is used as a gamma source [14], activity is approximately 590 GBq and energy 662 keV. After about 90 days exposure in GIF, the integrated dose was 0.52 Gy which is equivalent to approximately 4 years running at CMS, with a gamma rate at CMS being approximately 100 kHz/cm^2 [15].

Each GEM foil was initially cut as a square of 100 mm side and 60 μm thickness. Each square was cut into five strips, each of 20 mm width (figure 2). In addition, 20 mm of Kapton without copper layers was left extending out from the square to simulate a real GEM foil and to have an extra material that clamps of the machine grip. The holes were standard conical shape into the foil i.e. the outer and inner diameter was approximately 70 μm and 40 μm respectively [16]. The tests were performed in a controlled environment room. The samples were clamped into the INSTRON single column vertical testing system so that the clamps would end on the part of the foil where the copper layer begins.

In order to measure the holes diameter and their changes during streching, we used a Keyence VHX-1000 Digital Microscope. After loading the first sample in the machine, the sample orientation was checked and 100 mm gauge length was measured. The microscope was setup and focused in the centre of the sample horizontally, i.e. centre of two edges and vertically, i.e. centre of the two clamps. The machine was set to elongate the sample by a constant rate of five millimetres per minute, while the machine automatically adjusted the applied force to keep this rate constant. After starting the test it was observed that the microscope de-focused itself from the holes due to vertically motion of the sample, therefore it was manually focused to record the possible clearest video of the holes deformation. The test was finished when the sample started to tear. This process was repeated for each of the remaining samples one by one and holes deformation and tensile trends were recorded. The tensile tests were performed following the standard protocol (ASTM D882-02).

5 Results and discussion

Two types of tests are performed on each sample simultaneously. The tensile test, i.e. elongation under constant rate and increasing force till the rupture point (figure 3) shows the overall macroscopic trends of the GEM foil. Three sets of the samples, i.e. non-irradiated, gamma and neutrons irradiated are used for the foil tensile properties measurements, each set contains five samples.
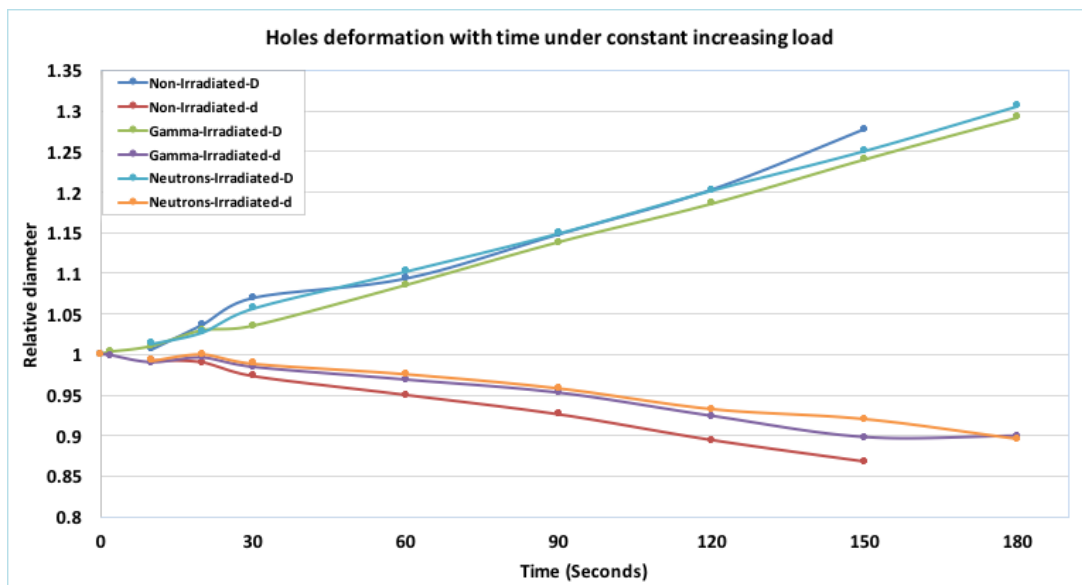
For the non-irradiated samples, the stress-strain curve in the range of approximately 40–60 MPa follows a typical elastic-plastic trend. All non-irradiated specimens ruptured between 111 MPa and 123 MPa. The gamma irradiated samples tensile trends have intermediate behavior between non-irradiated and neutrons irradiated from 35 MPa to 90 MPa, as shown in the figure 3. The rupture range of the gamma irradiated samples is 107 MPa to 132 MPa, higher than non-irradiated and much higher than neutrons irradiated. At lower stress, approximately from 20 MPa to 25 MPa, the non-irradiated, gamma and neutrons irradiated samples have an analogous behavior and after that range the curves started to spread out and each set follows a different curve.
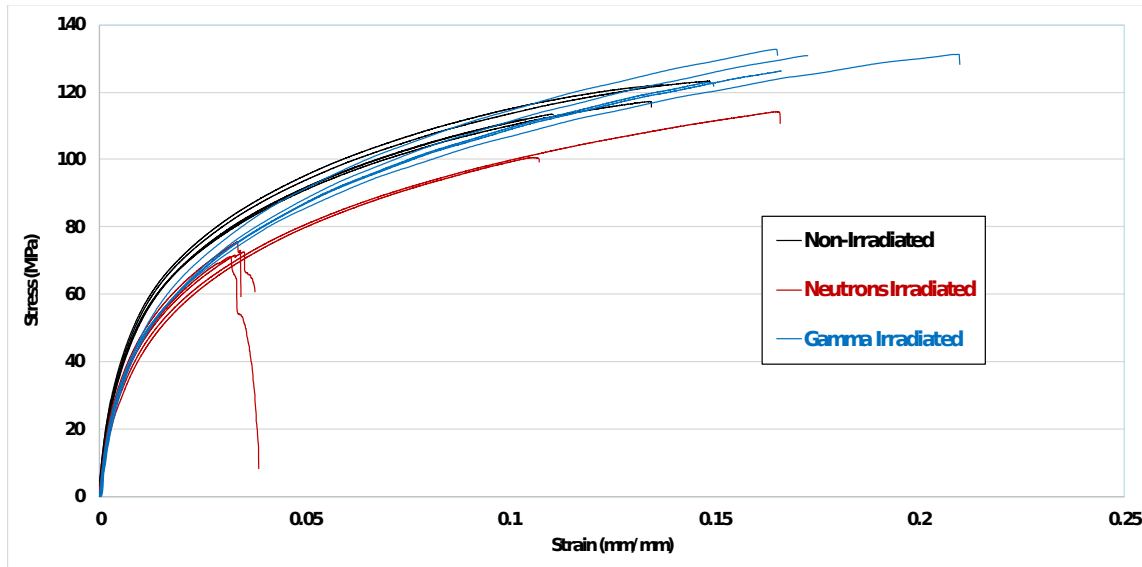

Figure 3. Tensile test trends comparison of non-irradiated, gamma, and neutrons irradiated samples.

The neutrons irradiated samples have a wide range of rupture stresses, i.e. three samples ruptured from 71MPa to 75MPa and two samples have however endured a much higher load of 100MPa and 112MPa before failure. Overall, the rupture mechanism is interpreted as due to cracks propagation generated by small imperfections randomly distributed around the holes during the coating and etching process. Exposure of samples to radiation is shown to anticipate the crack propagation, but the rupture mechanism remains basically a random process (figure 3). The spread of results provides an effective information on the statistical error and is suggestive of an intrinsic material non-uniformity.

The second set of measurements is the characterization of the GEM foils holes deformations by increasing the load with time. Three sets of samples were also used (non-irradiated, gamma and neutrons irradiated). To see the changes of the holes at the microscopic level, a video was recorded by using the digital microscope and the snapshots selected with time stamps 0, 10, 20, 30, 60, 90, 120, 150 and 180 seconds. Both major and minor diameter of six holes in each frame were measured and recorded. The relative diameters of non-irradiated, gamma and neutrons irradiated samples are shown in figure 4. The holes deformation trends of the three sets are similar at the start of the test till 20 seconds. After this point, the short diameter of the non-irradiated samples deformed slightly more than the irradiated.

Figure 4. Relative diameter in short (d) and long (D) diameter of the non-irradiated, gamma and neutrons irradiated samples and their trend lines. The original diameter of the sample at 0 seconds is set to 1. The long diameter (D) is parallel to the direction of stretching and short (d) is perpendicular to it, the specimens are stretched one by one with constant speed 5 mm/minute.
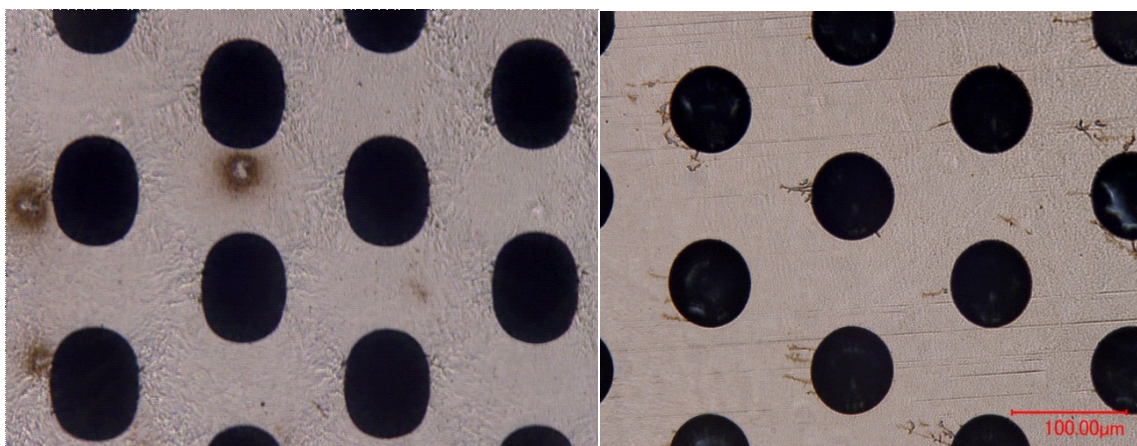

Figure 5. Left: shape of the holes in the GEM foils before the test started. Right: the deformation of the holes after 120 seconds (or approximately 110MPa) of the tensile test.

Overall the diameter of the holes does not undergo relevant deformation at the start of the test when samples length changes only approximately 2–3% from the original value e.g. before a 50MPa stress. As additional load is applied, the deformation of the holes increases faster. The longitudinal diameter (diameter of the hole parallel to the direction of the stretching) has a quicker rate of change than the transverse diameter (perpendicular to the direction of the stretching) and both ultimately were deformed substantially as shown in figure 4.

The non-proportional deformation of the holes versus the applied load was observed in the following sequence. After the yield point, the copper plasticization occurs on the edge of the holes
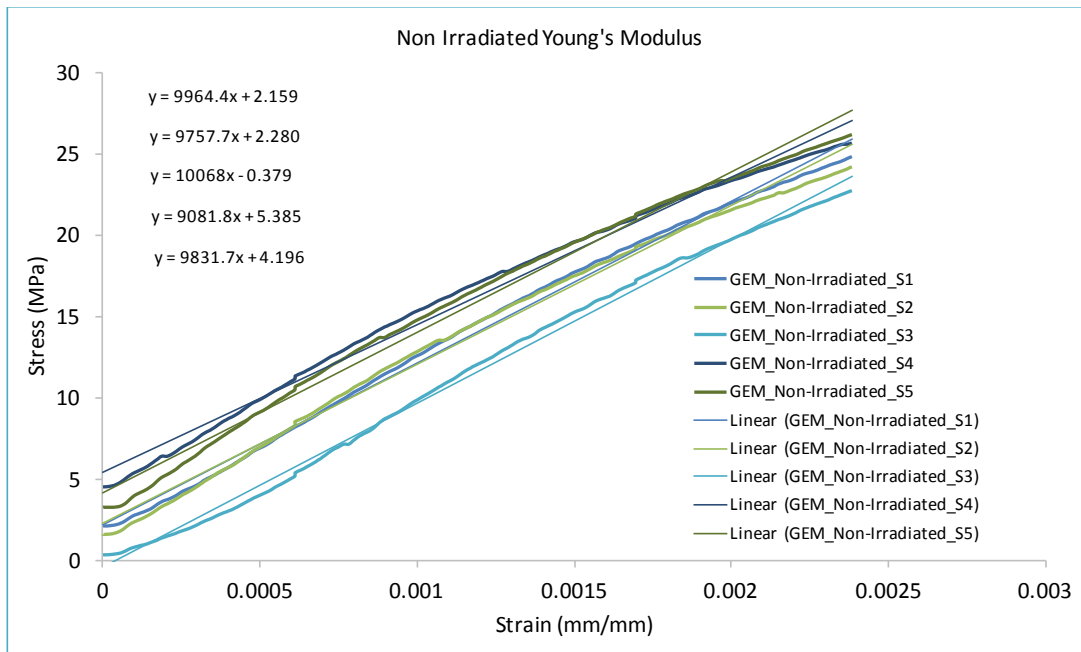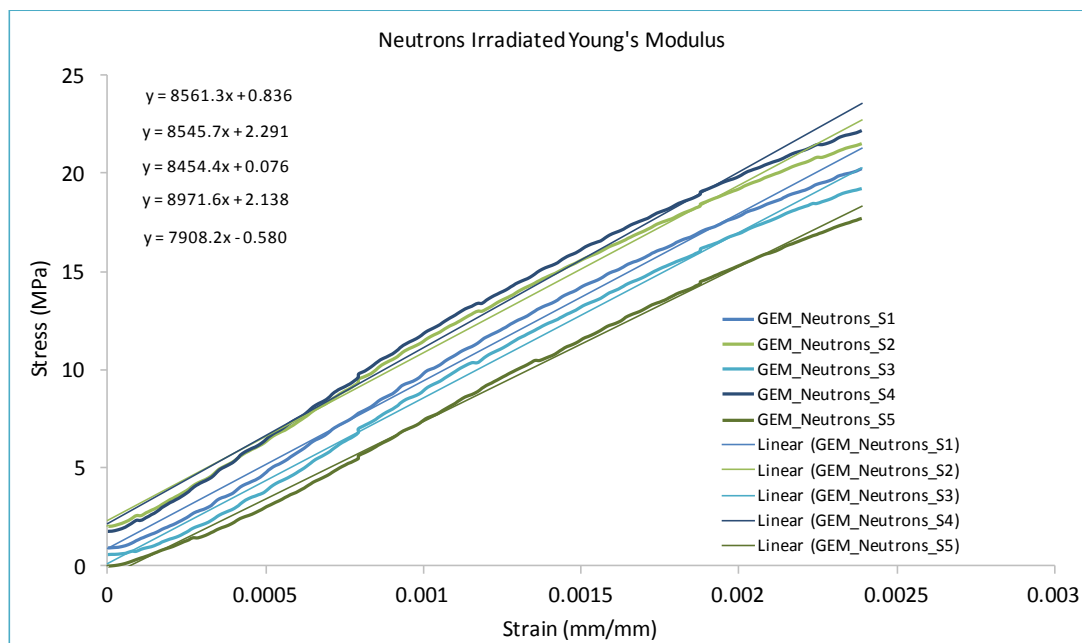
Figure 6. Young's modulus estimation of the non-irradiated GEM foil.
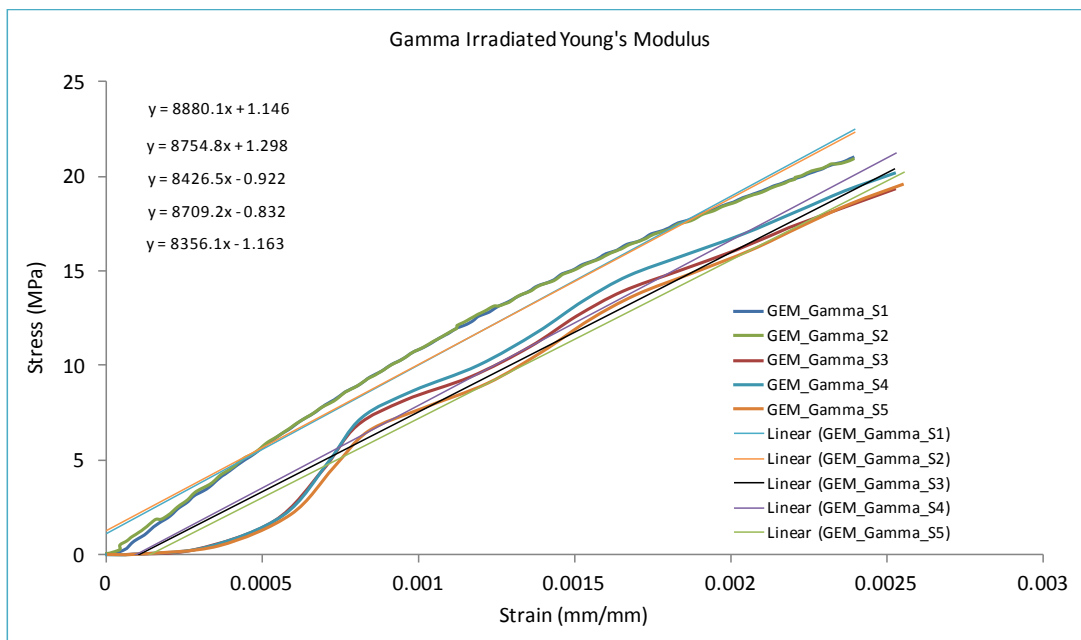
Figure 7. Young's modulus estimation of the gamma irradiated GEM foil.

Figure 8. Young's modulus estimation of the neutrons irradiated GEM foil.

which acts as an insulated region and by removing the load leaves the foil "apparently" in the elastic domain. If the load is increased beyond the plastic region, the deformation increases and when it involves the entire ligament (the shortest distance between two neighboring holes) then the plasticization is macroscopically evident.

By using the tensile test data, the Young's modulus of the GEM foil was estimated by applying a linear fit in the elastic region of the stress-strain curve. Linearity in the data is observed in the range of approximately from 17 MPa to 26 MPa and 0.0023 to 0.0025 for the stress and strain respectively, as shown in figure 6, 7, 8. In three gamma irradiated samples, wavy trends below 5 MPa are observed and are much reduced above 5 MPa and disappear completely beyond 20 MPa. The trends are attributed to a systematic effect in the specific test measurement. The average estimate of Young's modulus of non-irradiated, gamma and neutrons irradiated samples is 9.73 GPa, 8.62 GPa and 8.47 GPa respectively, which is suggestive of a material degradation even in the elastic range. The neutrons degradation effects are more significant than the gamma effects. In literature [17] the ion irradiation effects of polyimide are reported, as polyimide is a major component of the GEM foil. The average Young's modulus of fifteen GEM foil samples is estimated approximately 8.94GPa. The GEM foil elasticity, i.e., becomes much smaller than the Kapton elasticity [18] just by introducing a thin layer (5 μm) of the copper at each side of the Kapton: the mechanical behaviour of a compound is dominated by 16 % copper over 84% Kapton.

6 Summary

Tensile tests were performed on three sets of the GEM foil samples. Each set contained five samples. The first set (non-irradiated) was used as a reference; the second set (neutron irradiated) simulated the radiation exposure that the foil would undergo over approximately 10–12 years at the CMS

detector at full luminosity; the third set (gamma irradiated) absorbed the dose equivalent to 4 years of CMS running. All sets were stretched at a constant rate of 5 mm per minute until the failure point. The macroscopic elongation of the foil over increasing stress was measured. The change in the diameter of the GEM foil holes was recorded by a digital microscope. It was seen that the diameter of the holes changed very slowly at lower load but it started to change comparatively fast as the stress applied on the samples crossed 42 MPa–50 MPa.

The non-irradiated samples experienced failure at the stress range of 111 MPa–132 MPa. A much larger spread in the failure range of the neutrons irradiated samples was observed. Three neutrons irradiated samples failed in the range of 71 MPa–75 MPa, However, two samples failed at higher stress about 100 MPa and 112 MPa. This kind of different behavior was attributed to small random imperfections around the holes caused by the coating and etching process which could be exaggerated by the irradiation process (section 5).

Basically neutrons reduce the strength in the elastic region and also toughness in elastic-plastic and plastic region. The gamma exposure reduced the strength of the material in elastic region which was less than neutrons but in elastic-plastic and plastic region the material toughness was increased even from the non-irradiated samples. This difference can be seen from Young's modulus values (elastic region effects are prominent) and in figure 3 (elastic-plastic and plastic effects are prominent). This degradation phenomenon was related to the molecular structure modification due to irradiation which was beyond the scope of our study in this paper.

The Young's modulus of the non-irradiated GEM foil composite material was approximately 9.74 GPa and for gamma and neutrons it was 8.62 GPa and 8.47 GPa respectively. In this study the unidirectional dynamic stress effects at the holes and tensile properties were studied. Further studies are ongoing to characterize the long term stability (creep) of the GEM material under constant stress.

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