# Solar physics on LISA

Catia Grimani[1], Michele Fabi[2]

***Abstract*— LISA (Laser Interferometer Space Antenna) is the first interferometric device devoted to the detection of low frequency gravitational waves in space. In spite of this primary goal for the experiment, LISA and its precursor mission LISA-Pathfinder (LISA-PF) will allow us to study important topics of solar and cosmic-ray physics with particle monitors that will be placed on board. In particular, solar energetic protons and helium nucleus mapping over two degrees in longitude will be carried out on the three LISA spacecraft. In case electron monitoring will be added, forecasting of upcoming solar protons will be possible as well. These measurements will provide precious clues to improve modelizations of impulsive and gradual phases of strong solar events and for space weather investigations.**

## I. INTRODUCTION

Space experiments require a detailed study of their environment at the time they will be held in order to be fully successful. In particular, for LISA see [1] and [2]. At the same time, the important role that LISA can play for solar physics and space weather investigations was pointed out for the first time in [3]. LISA will allow us to carry out for the first time solar particle measurements with energies above 100 $MeV(/n)$ at small steps in longitude. In case of solar electron detection on board, improvements to modelizations of both impulsive and gradual phases of strong solar events and particle propagation processes will be possible on the basis of LISA observations [4] [5]. In this paper we report an estimate of incident galactic cosmic-ray spectra at the time of both LISA missions. The number of solar expected events with fluences ranging between $10^6$ and $10^{11}$ $protons/cm^2$ above 30 $MeV$ on the basis of Nymmik model [6], [7] are studied as well.

## II. THE LISA MISSIONS

LISA is the first interferometer devoted to the detection of gravitational waves in space in the frequency range $10^{-4}$ - $10^{-1}$ $Hz$. It consists of three spacecraft placed $5 \times 10^6$ $km$ apart at the corners of an equilateral triangle. The formation center of mass lies on the ecliptic. Each spacecraft hosts two inertial sensors. The heart of the inertial sensors are cubic gold-platinum test masses. The test masses constitute the interferometer mirrors. Their position is detected with gold plated electrodes. Energetic solar and cosmic rays charging the test masses are one of the most important sources of noise for the experiment. Ultraviolet light beams will be used to discharge the proof masses ([8] and references therein).

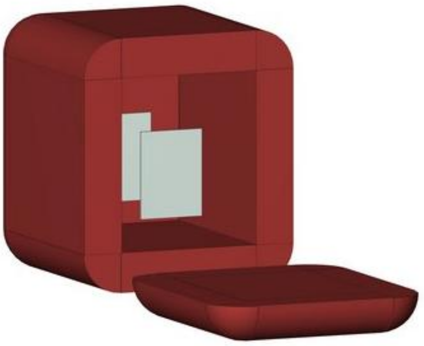

Fig. 1. LISA-PF radiation monitor set-up. Silicon detectors are sketched inside the shielding copper box.

LISA will likely fly around 2018. The maximum mission duration is expected to be 10 years.

The LISA-PF consists of one satellite hosting two test masses to be sent into orbit around L1 in 2011. LISA-PF target sensitivity is one order of magnitude smaller than LISA [9] . Data will be gathered for six months.

Radiation detectors monitoring cosmic-ray and energetic solar particle fluxes will be placed on board both missions. The design was finalized for LISA-PF only [10]. Two silicon wafers of 1.4 x 1.05 $cm^2$ area will be located in a telescopic arrangement at a distance of 2 $cm$. The geometrical factor of each silicon layer for an isotropic incidence is 9 $cm^2$ $sr$ and for coincidence events is about one tenth of it. The silicon telescopes are placed inside a copper box of 6.4 $mm$ thickness in order to limit the energy of protons and helium nuclei traversing these detectors to a few tens of $MeV(/n)$ (see figure 1). This energy cutoff is similar to the minimum energy needed to the most abundant components of cosmic rays to penetrate the test masses. No electron monitoring is allowed on LISA-PF.

## III. SOLAR ACTIVITY AT THE TIME OF THE LISA MISSIONS

Solar activity and the Global Solar Magnetic Field (GSMF) polarity modulate galactic cosmic rays (GCR) fluxes [2]. The symmetric model in the $force\ field\ approximation$ by Gleeson and Axford [11] allows us to estimate the energy spectra of cosmic rays at a distance $r$ from the Sun, at a time $t$ assuming time-independent interstellar intensities. An energy loss related to the charge of cosmic-ray particles and a $solar\ modulation\ parameter$, $\phi$, above about 100 $MeV$

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[1] Institute of Physics, University of Urbino, INFN Sez. Florence, Via S. Chiara, 27, 61029 Urbino (PU), Italy, catia.grimani@uniurb.it

[2] Institute of Physics, University of Urbino, Via S. Chiara, 27, 61029 Urbino (PU), Italy, m.fabi@campus.uniurb.it

are assumed. This model does not include the GSMF polarity influence on the drift of positive and negative particles in the heliosphere. During positive heliomagnetic field polarity epochs, positive charge particles reach the Earth most likely from the polar regions of the heliosphere, while negative charge particles come mainly from the ecliptic regions along the Heliospheric Current Sheet (HCS). An opposite situation holds during negative magnetic field polarity periods. Particles propagating along the HCS are more modulated with respect to those coming from the poles.

A correlation between high solar activity and solar particle event occurrence is observed as well. Strong solar events generate proton fluxes in the energy range up to a few hundreds of MeV various orders of magnitude larger than the Galactic ones (see for example [3]). Charge deposited on test-masses increases accordingly [12]; [13]. A reliable simulation of the test-mass charging can only be achieved if a correct estimate of the bulk of the incident Galactic and solar cosmic rays at the time of LISA-PF and LISA missions is carried out.

In table I we have reported the expected solar spot number for the next two solar cycles. Minimum and maximum solar spot number for the cycle 24 were considered [14]; [15]. For the cycle 25 an average SS number prediction [16] was used.

TABLE I

EXPECTED SOLAR SPOT (SS) NUMBER DURING THE NEXT TWO SOLAR CYCLES.

| | Year | Minimum SS | Maximum SS | Average SS |
|---|---|---|---|---|
| Solar Cycle 24 | | | | |
| | 2009 | 9 | 39 | |
| | 2010 | 36 | 127 | |
| | 2011 | 57 | 220 | |
| | 2012 | 68 | 195 | |
| | 2013 | 67 | 149 | |
| | 2014 | 54 | 122 | |
| | 2015 | 44 | 88 | |
| | 2016 | 24 | 63 | |
| | 2017 | 11 | 16 | |
| | 2018 | 5 | 15 | |
| Solar cycle 25 | | | | |
| | 2019 | | | 4 |
| | 2020 | | | 17 |
| | 2021 | | | 37 |
| | 2022 | | | 56 |
| | 2023 | | | 63 |
| | 2024 | | | 60 |
| | 2025 | | | 50 |
| | 2026 | | | 37 |
| | 2027 | | | 23 |
| | 2028 | | | 11 |
| | 2029 | | | 5 |

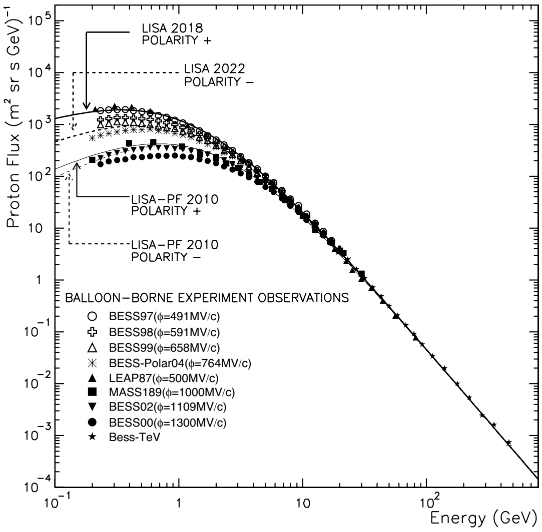

Fig. 2. Cosmic-ray proton differential energy flux measurements carried out by the BESS experiment during various levels of solar activity and solar polarity epochs. Thick and thin curves represent the input fluxes at the time of LISA and LISA-PF, respectively. Details of flux interpolations are reported in [2].

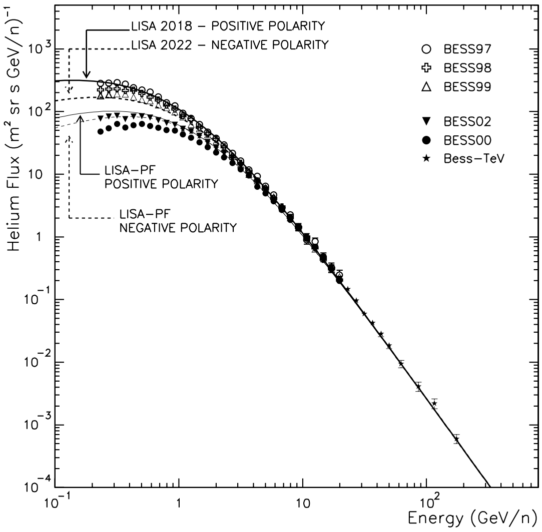

Fig. 3. Same as figure 2 for helium nuclei.

LISA-PF is supposed to take data at solar maximum ($\phi = 1100MV/c$) near the next polarity change from $-$ to $+$. The first part of the LISA mission should be held at solar minimum (reasonably, $\phi = 550MV/c$) even if it might be extended through the maximum of the solar cycle 25 (see [2] for details). Galactic proton and helium expected incident fluxes at the time of the two missions are reported in figures 2 and 3.

Test-mass charging and radiation monitor countrates were discussed in [2] and [17].

## IV. EXPECTED SEP EVENTS DURING LISA-PF AND LISA

In order to evaluate the overall performance of LISA and LISA-PF and to optimize the design of diagnostic detectors to be placed on board we estimate the expected number of solar energetic particle (SEP) events during the two missions

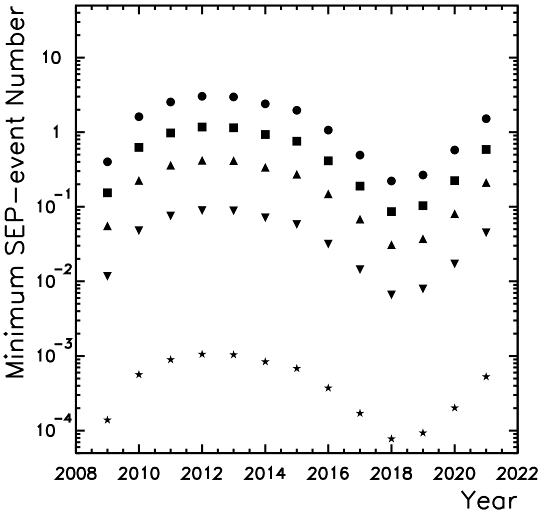

Fig. 4. Expected minimum number of SEP events during solar cycle 24 per interval of fluence (solid dots $10^6 - 10^7$ $protons/cm^2$; solid squares $10^7 - 10^8$ $protons/cm^2$; solid triangles $10^8 - 10^9$ $protons/cm^2$; solid upside down triangles $10^9 - 10^{10}$ $protons/cm^2$; solid stars $10^{10} - 10^{11}$ $protons/cm^2$). LISA-PF is supposed to take data for six months in 2011.

focusing on the role of $e^-$ of solar origin.

Nymmik [6], [7] has found that the SEP fluence distribution follows a power-law trend with an exponential cutoff for large fluences. This model applies to solar proton fluences ranging between $10^6$ and $10^{11}$ $protons\ cm^{-2}$ for particle energies above 30 $MeV$. The Nymmik results were inferred from the analysis of the spacecraft IMP-7 and 8 measurements of SEP events during the solar cycles 20-22 and from proton fluxes estimated on the basis of radionuclide observations in lunar rocks generated in the last few million years.

We estimated the number of SEP events in individual intervals of fluence during the next two solar cycles according to the Nymmik modelization and the number of solar spots reported in table I. The method is reported in the following:

(i) we determined the number of SEP events,$< n >$, for each year on the basis of solar spot number predictions ($< w >$):

$$< n >= 0.0694 < w > \tag{1}$$

(ii) a normalization constant C was found for each case integrating the function

$$dn = C\phi^{-1.41} e^{-\phi/\phi_c} d\phi \tag{2}$$

and by equating it to the number of SEP events calculated in (i). $\phi_c$ was assumed equal to $4{\times}10^9$.

(iii) Finally, after constant C determination, we estimated the number of events per fluence interval.

Results are reported in figures 4 and 5 for the solar cycle 24 and in figure 6 for the solar cycle 25.

We expect an average number of 4.4 SEP events during the six months of data taking of the LISA-PF mission in the whole range of considered fluences. In case it will be confirmed that solar cycle 25 will be a weak one, a maximum of 5 SEP events per year are estimated to be observed on LISA.

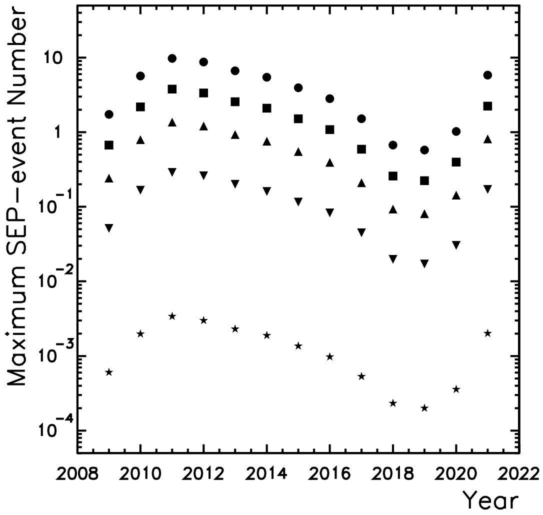

Fig. 5. Same as fig. 4 for the expected maximum number of SEP events.

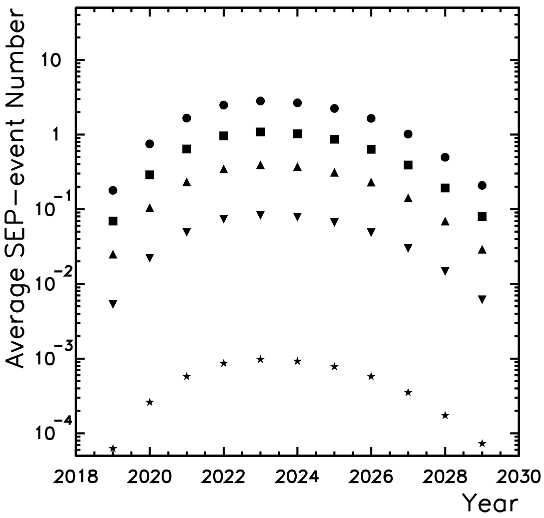

Fig. 6. Same as fig. 4 for the expected average number of SEP events during the solar cycle 25.

It is worth to point out that a double peak and gap (Gnevyshev gap; [18], [19]) form is often observed at solar maximum in the distribution of some parameters related to solar activity such as sunspot number, sunspot area, mean fluence and mean peak fluxes. In case Gnevyshev gaps at solar maximum will be present during the LISA missions, the number of solar events predicted in this paragraph during the same period might be reduced by a maximum of a few tens % [20].

## V. ADVANTAGES OF ELECTRON DETECTION ON LISA

The possibility to forecast strong solar events on board LISA might help in optimizing the test-mass discharging methods and to extend the experiment live time for data analysis.

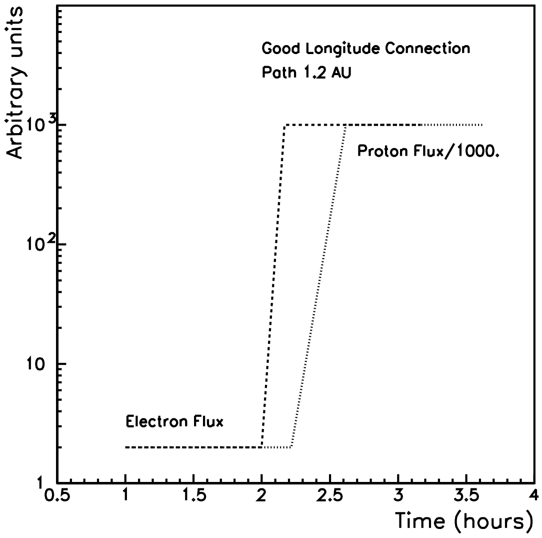

Fig. 7. Electron and proton fluxes to be observed on LISA as a function of time at the occurrence of a solar event magnetically well connected to the experiment and 0 pitch angle.

The proposition to place particle detectors on board the LISA mission for proton, helium and electron identification was reported in [1]. Solid state detectors with anticoincidence and fast pulse-height analysis for electron and ion separation were suggested.

COSTEP on SOHO and GOES 8 data indicate that relativistic electrons reach 1 AU always before the bulk of non relativistic solar ions allowing their forecasting. Moreover, intensity increases of electrons and protons show similar trends depending only on the magnetic longitude difference between flare and observer (magnetic connection). The early electron intensity and increase versus time can be used to infer upcoming proton intensity [4].

Assuming an ideal propagation along the interplanetary magnetic field lines (pitch angle equal to 0) and a path of 1.2 $AU$ for a magnetically well connected event, protons propagate with time delays ranging between 13 and 3 minutes for energies between 100 $MeV$ ($\beta$=0.43) and 500 $MeV$ ($\beta$=0.76) with respect to electrons. In case MeV electron detection on board LISA will be allowed, electron and proton (above 100 $MeV$) flux increases would appear as shown in figure 7 (fluxes were normalized). Thirteen minute warning will be allowed before the proton onset would be registered by a radiation-monitor like that operating on LISA-PF. We point out that this is a worst case scenario. For particle propagation along a path of 2 $AU$ corresponding to a well connected event with a non-zero pitch angle, incoming electron and proton fluxes would appear on the experiment as in fig. 8.

The Posner work reveals that an average (maximum) warning time of approximately 30 minutes (1 hour) can be given of upcoming solar protons and helium nuclei above 100 $MeV$(/n).

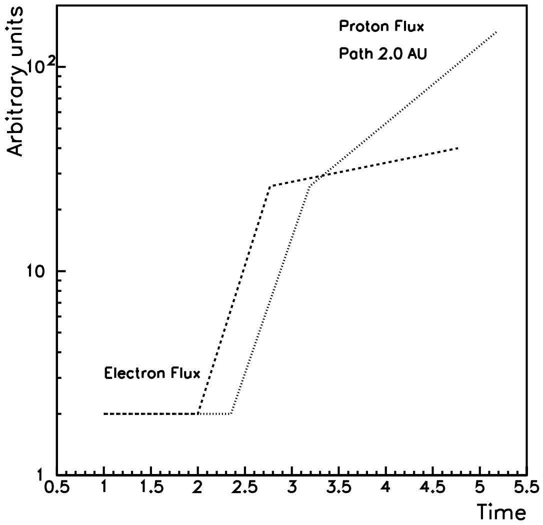

Fig. 8. Electron and proton fluxes to be observed on LISA as a function of time for a particle path of approximately 2 AU.

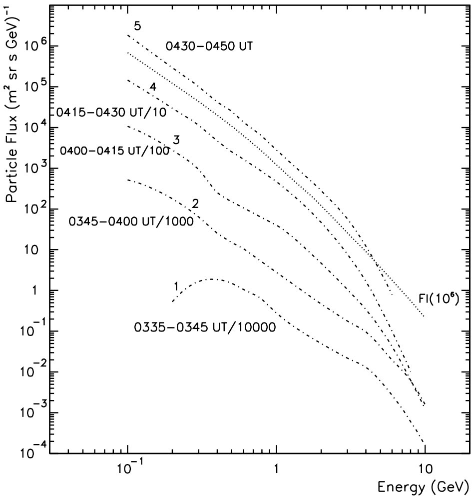

Fig. 9. Proton spectra observed during the May 7th 1978 flare (dot-dashed lines). The dotted line indicate the expected peak flux for an event of $10^6$ $protons/cm^2$ fluence.

## VI. LISA-PF RADIATION MONITOR PERFORMANCE

The LISA-PF radiation monitor performance was simulated with the Fluka Monte Carlo Program [21]. We used for this simulation the same interval of time (614.4 s) corresponding to the rate of data transmission to ground [10]. GCR input fluxes and a sample flare were considered.

In figure 9 we have reported the observed proton energy spectra during the solar event of May 7th 1978. Curves 1 to 5 show the evolution of the particle spectrum for the indicated intervals of time [22].

The countrate variations on each silicon layer is reported in table II. Flux numbers are chosen like in fig. 9. In figs. 10, 11 and 12 we have reported the ionization energy losses of coincidence GCR and proton fluxes associated with the May

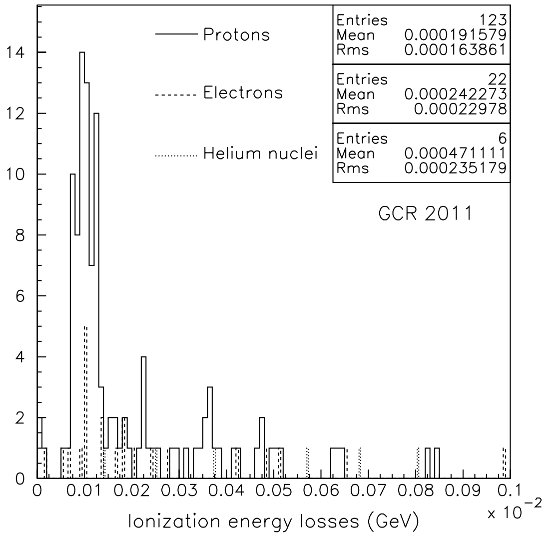

Fig. 10. Galactic cosmic-ray ionization energy losses in the radiation monitors. Particles traversing both silicon wafers are considered.

7th 1978 event at the onset and at the peak. It is possible to notice that we are able to follow the evolution of the May 7th 1978 event using both silicon detector countrates and ionization energy deposits. We aim to develop data analysis criteria that will allow us to reliably infer from radiation monitor observations the intensities of solar particle fluxes incident on the apparatus at all times. Contemporary test-mass charging will be estimated accordingly.

TABLE II

LISA-PF RADIATION MONITOR COUNTRATE BEFORE AND DURING THE MAY 7TH 1978 EVENT.

| Input fluxes | Radiation monitor countrate (counts/s) |
|---|---|
| GCR | 2.0 |
| Flux 1 | 10.5 |
| Flux 2 | 47.9 |
| Flux 3 | 68.2 |
| Flux 4 | 77.9 |
| Flux 5 | 104.8 |

## VII. CONCLUSION

GCR fluxes and strong solar event occurrence at the time of the LISA missions were studied. LISA-PF-like radiation monitors for proton and helium nuclei will provide precious clues to model the dynamics of strong solar events. However, only solar electron detection on board will allow us to forecast upcoming solar ions for space weather investigations. These measurements will be of major importance for test-mass discharging and data analysis optimization during the LISA mission.

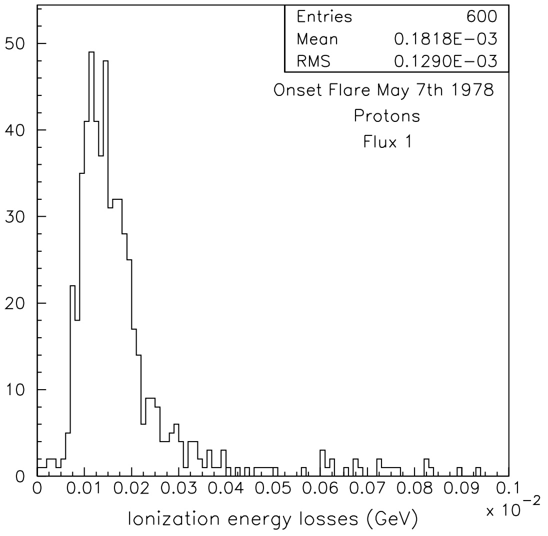

Fig. 11. Ionization energy losses for coincidence protons in the radiation monitors at the onset of the May 7th 1978 flare.

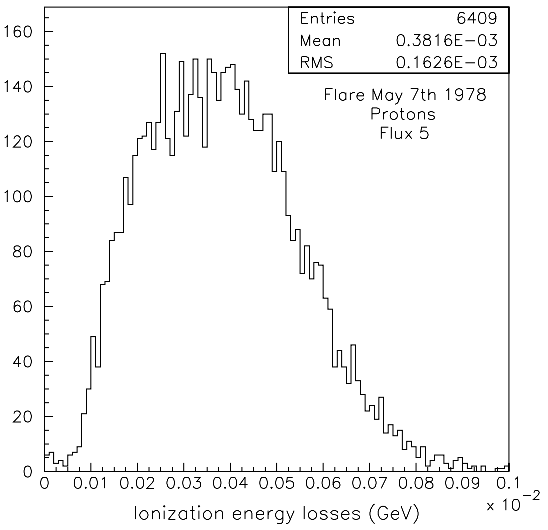

Fig. 12. Same as figure 11 at the peak of the May 7th 1978 flare.

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