18th WRMISS @ Budapest, Hungary
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* Long-term dose variations in the ISS Piers-module measured with passive dosimeters *

(Extended analysis of Radiat.Meas., 49 (2013) 95)

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* Radiation environment of Lower Earth Orbit *

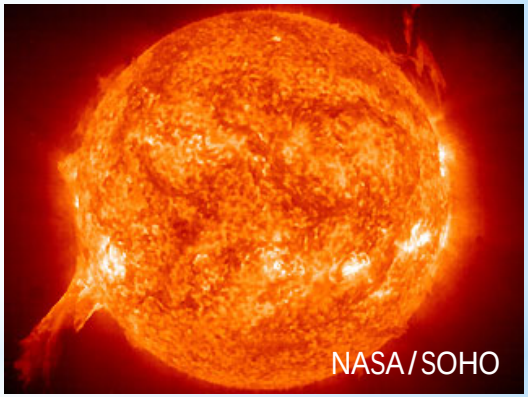
Mixed radiation fields of:

- Galactic cosmic rays (GCR) : Heavy ions (p~Fe), energy~1 GeV/n
- Solar energetic particles (SEP) : Proton, energy~100MeV
- Trapped particles (TR) : Proton and Electron, energy<250MeV
- Secondary particles (SP) : Neutron, Projectile & Target fragments etc

Radiation dose rate varies depending on:

1) Solar activity (11-yr cycle)
   - GCR intensity varies with negative correlation
   - SPE frequency associated with solar flares and CMEs

2) Orbital parameters of the ISS
   - Altitude and orbital location relative to the Earth
   - Attitude (orientation)
   - Shielding distribution of inside



Radiation environment gradually and sometimes impulsively varies:

→ Constant dose monitoring in the ISS is highly needed for control of the crew health and safety

* Radiation dose monitoring on the ISS *

Passive dosimeter (This work)	Active dosimeter
Luminescence + Nuclear track detectors - TLD, OSLD, RPLD - CR-39, Nuclear emulsion	Proportional gas counters - TEPC, R-16
Bubble detectors	Silicon detectors - DOSTEL, ALTEA, Liulin, DB-8, Medipix

Advantages:

- Being small and lightweight, low cost and no need of electric power supply

→ Easy handling and possible to distribute it any location

Disadvantages:

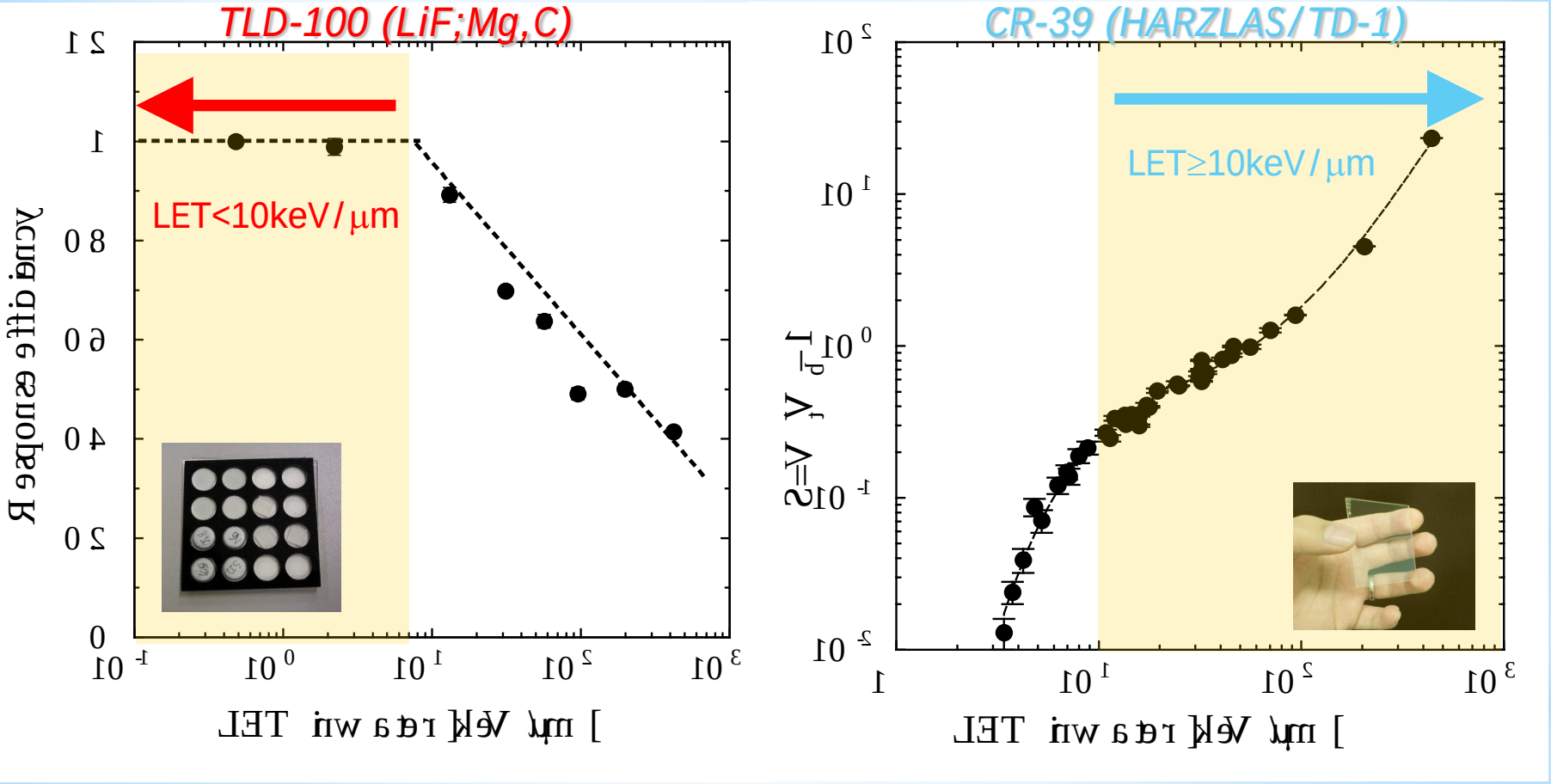
- Incapable of being read out in real time (available as averaged dose)

→ No information on time variations of dose rate in the dynamically changing space radiation environment

Passive dose data set measured at same location through several different periods provide the gradual (half year scale) dose variation

i.e. Roughly we can see dose variation with even passive dosimeters)

* Passive dosimeters (TLD-100 and CR-39) *



- Response of TLD for LET<10keV/μm is almost constant, while response for high LET strongly depends on LET
- CR-39 provides LET spectrum for high LET (≥10keV/μm) particles

* Total dose estimation *

Covering wide dynamic range of LET:

(1) Dose for LET<10keV/μm is obtained by TLD, while dose for LET>10keV/μm from TLD is removed by CR-39 data

(2) Dose for LET≥10keV/μm is obtained by CR-39

Absorbed dose: D_{Total}:

$$D_{Total} = D_{\le 10keV/\mu m} + D_{>10keV/\mu m}$$
$$= \left(D_{TLD} - \kappa D_{CR-39}\right) + D_{CR-39}$$
$$= D_{TLD} + (1-\kappa) D_{CR-39}$$

Dose equivalent: H_{Total}:

$$H_{Total} = D_{\le 10keV/\mu m} + H_{>10keV/\mu m}$$
$$= \left(D_{TLD} - \kappa D_{CR-39}\right) + H_{CR-39}$$

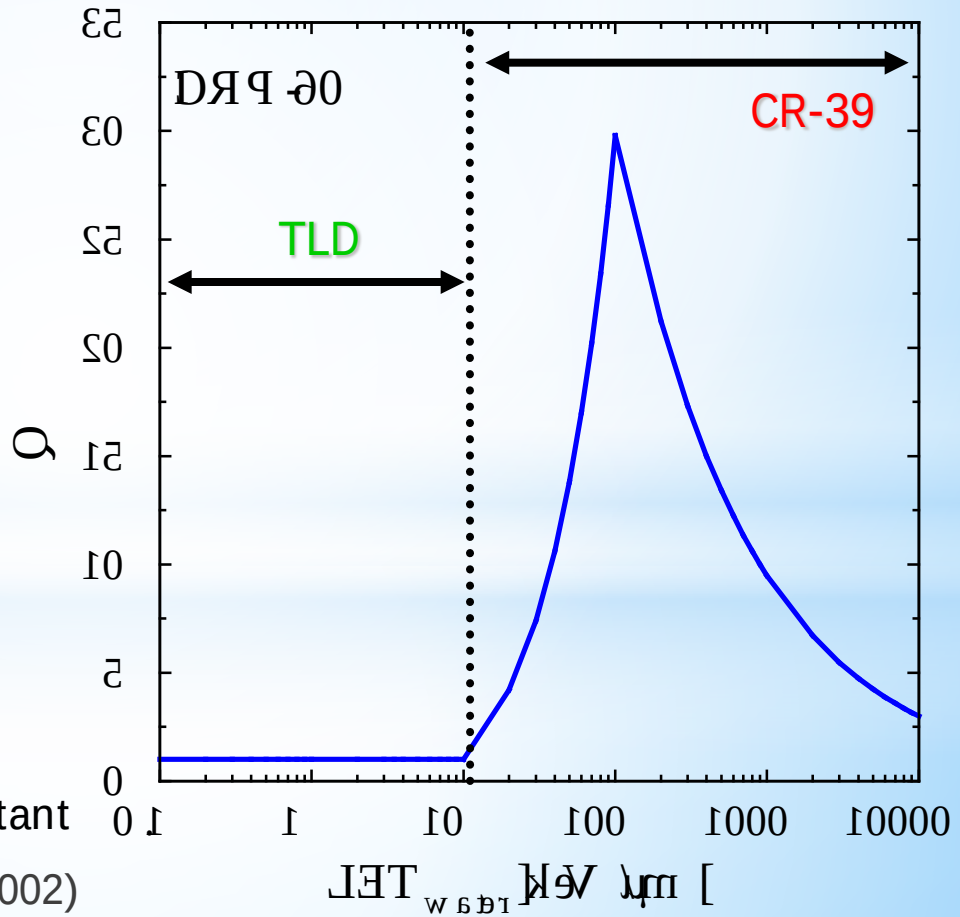
Mean quality factor: $<Q_{Total}>$

$$< Q_{Mean} > = H_{Total} / D_{Total}$$

k: proportional constant

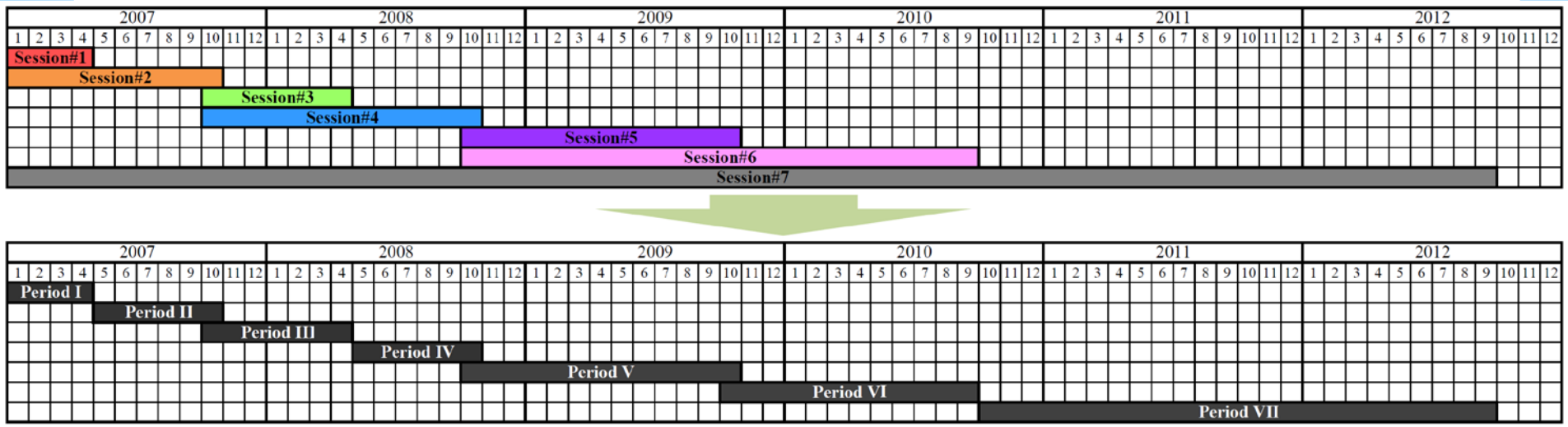
(Doke et al., 1995, Benton & Benton, 2002)

Quality Factor-LET relationship (ICRP-60)



* Space radiation exposure onboard ISS *

- Installed in Piers-1 module through 7 sessions with different terms between 2007 and 2012
- Configuration and location of dosimeter package were almost same through all sessions



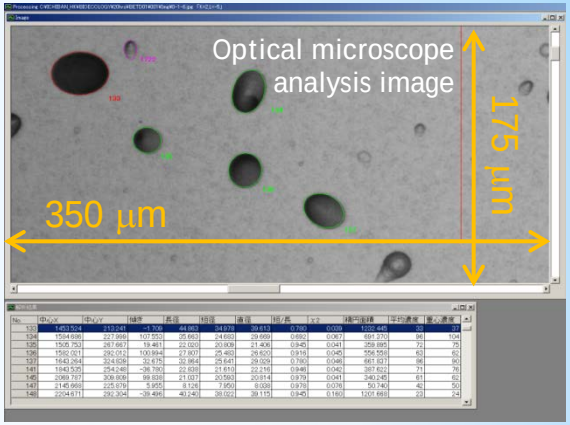
By subtracting the overlapping terms during 7 sessions, the exposure terms can be divided into 7 periods (I - VII)

	Dividing method	DOY term since Jan. 1, 2007	Duration [days]
Period I	= Session #1	19 – 111	92
Period II	= Session (#2 – #1)	111 – 295	184
Period III	= Session #3	283 – 475	192
Period IV	= Session (#4 – #3)	475 – 663	188
Period V	= Session #5	651 – 1015	364
Period VI	= Session (#6 – #7)	1015 – 1364	349
Period VII	= Session (#7 – #2 – #4 – #6)	1364 - 2087	699

* CR-39 analysis *

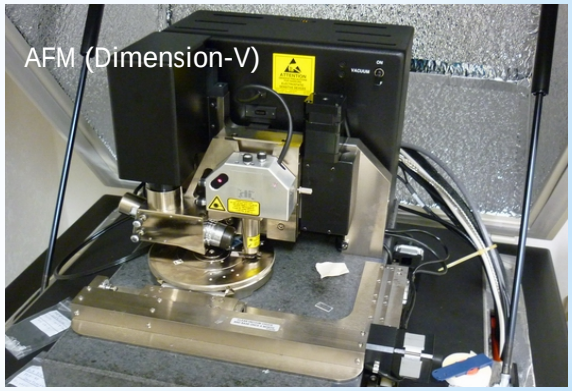
1) Optical microscope analysis for <1 yr exposure samples:

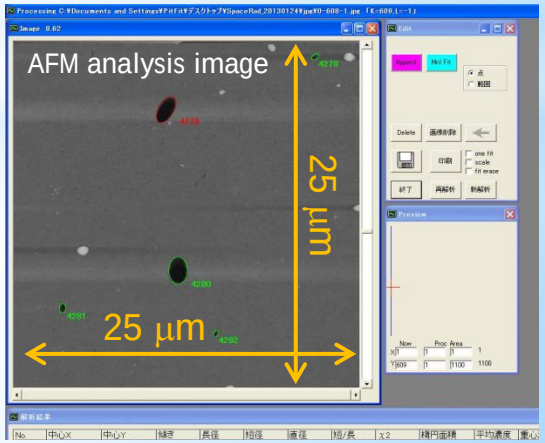
- Detectors of Session#1~#5 (0.5 ~1 yr exposure) have been etched for 8 hrs in 7N NaOH 70 °C
- Mean bulk etch was 14.3 μm
- Analyzed with HSP-1000 and PitFit software
- Scanned image area: 4 mm^2
- Pixel resolution: 0.35 μm/pix



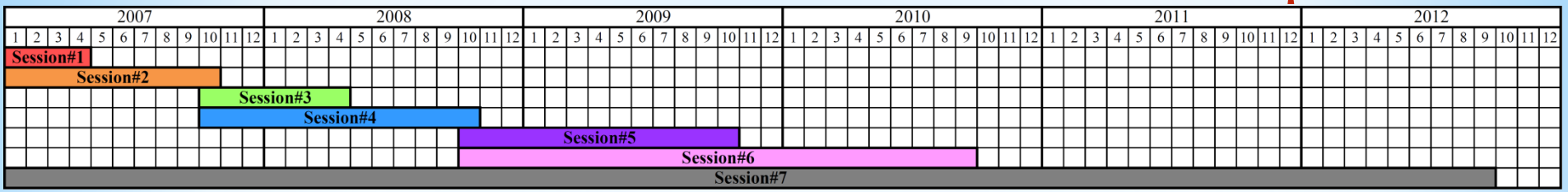
2) Atomic force microscope (AFM) analysis for long exposure samples:

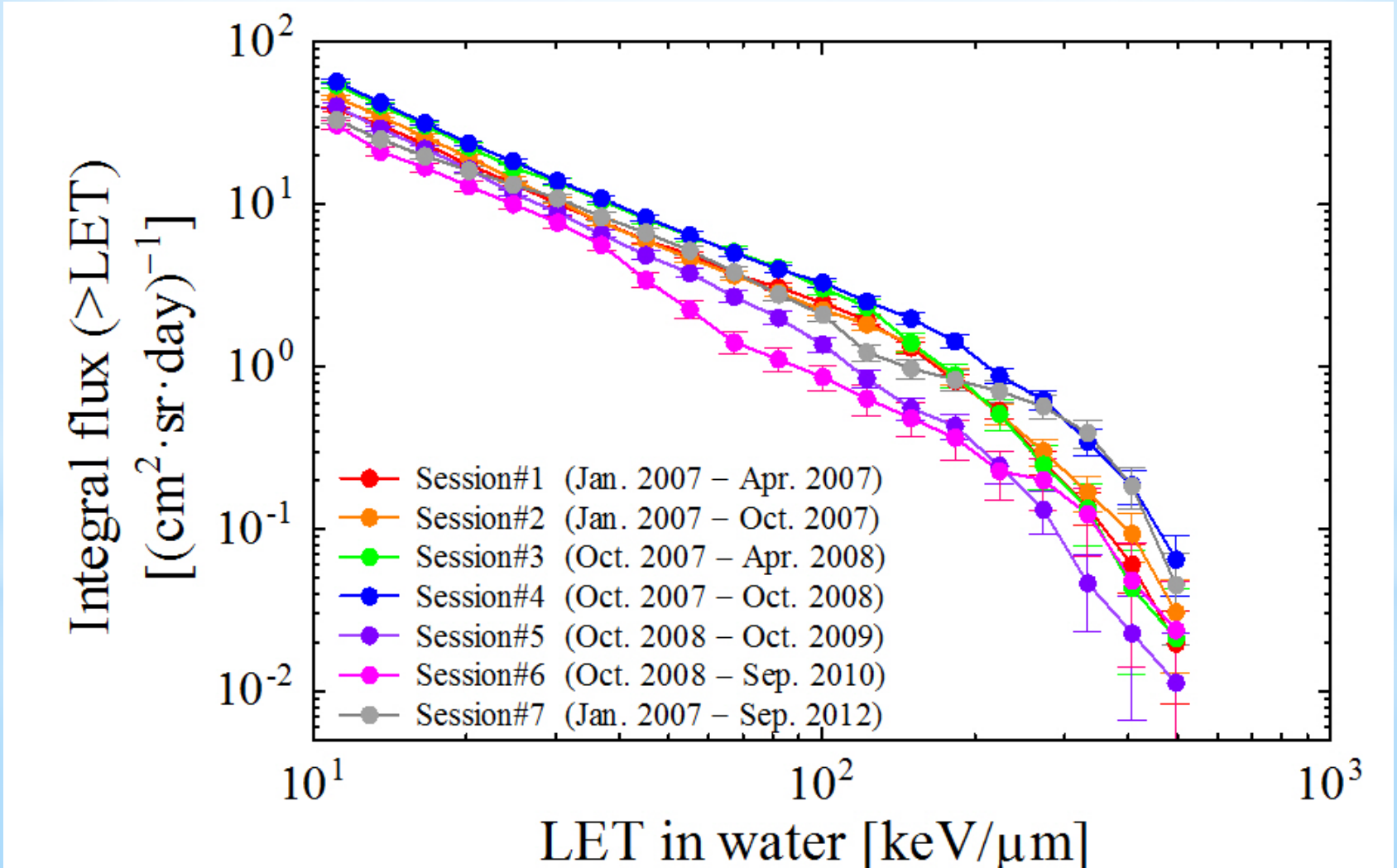
- Detectors of Session#6 and #7 (2 and 5.5 yr exposures) have been etched for 0.5 hrs in 7N NaOH 70 °C
- Mean bulk etch was 1.056 μm
- Analyzed with AFM (Veeco/Demension-V) and PitFit
- Scanned image area:
  1.0 mm^2 (1564 images) for Session#6 (2 yr exp.)
  0.5 mm^2 (851 images) for Session#7 (5.5 yr exp.)
- Pixel resolution: 24 nm/pix





* LET spectrum variation in 7 sessions *



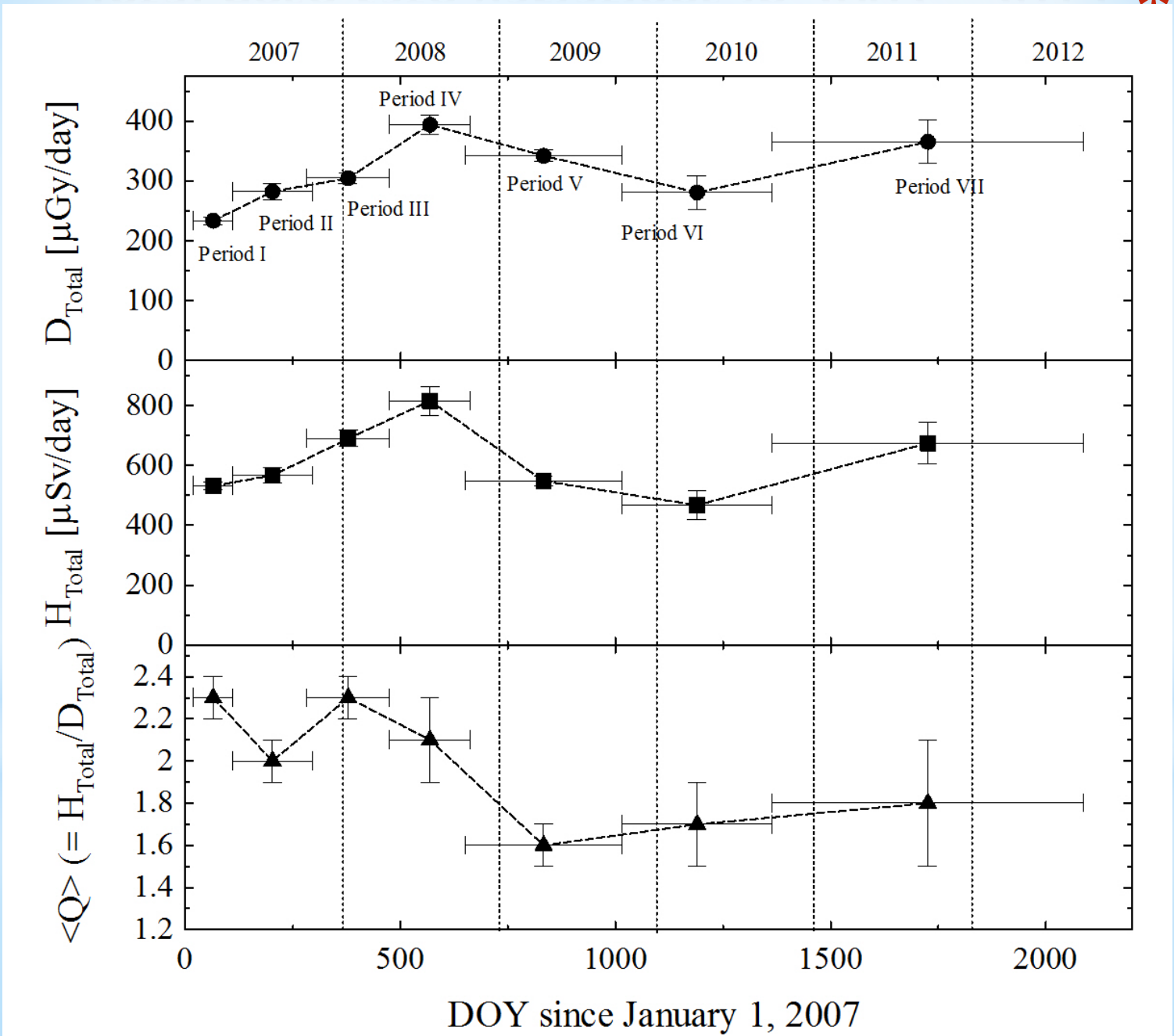


* Total dose results (TLD + CR-39) *

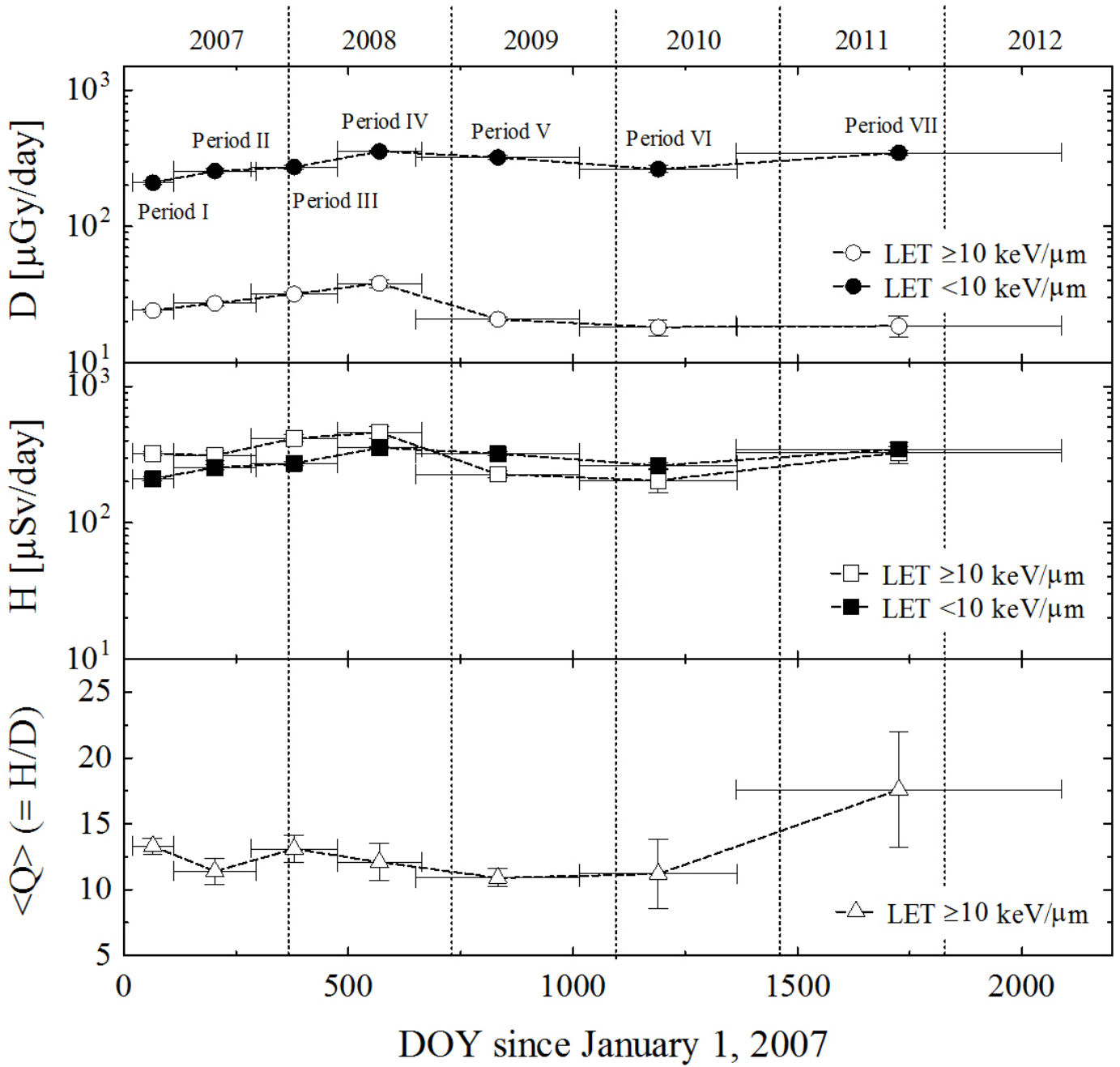
	Duration	D_{Total} [mGy]	H_{Total} [mSv]	<Q> ($=H_{Total}/D_{Total}$)
Session#1	Jan.07 – Apr.07 / 92days	21.5 ± 0.6	48.9 ± 1.3	2.3 ± 0.1
Session#2	Jan.07 – Oct.07 / 276 days	73.5 ± 2.4	153.2 ± 4.8	2.1 ± 0.1
Session#3	Oct.07 - Apr.08 / 191 days	58.5 ± 1.7	132.4 ± 5.2	2.3 ± 0.1
Session#4	Oct.07 – Oct.08 / 380 days	132.5 ± 2.5	285.7 ± 7.6	2.2 ± 0.1
Session#5	Oct.08 – Oct.09 / 364 days	124.5 ± 3.6	199.5 ± 5.9	1.6 ± 0.1
Session#6	Oct.08 – Sep.10 / 713 days	222.6 ± 9.0	362.5 ± 15.8	1.6 ± 0.1
Session#7	Jan.07 – Sep.12 / 2068 days	684.2 ± 23.5	1272.7 ± 44.4	1.9 ± 0.1

	Divided duration	D_{Total} [μGy/day]	H_{Total} [μSv/day]	<Q> ($=H_{Total}/D_{Total}$)
Period I	Jan.07 – Apr.07 / 92days	233.8 ± 6.6	531.4 ± 14.2	2.3 ± 0.1
Period II	Apr.07 – Oct.07 / 184 days	282.4 ± 13.5	566.8 ± 27.3	2.0 ± 0.1
Period III	Oct.07 - Apr.08 / 191 days	304.6 ± 8.9	689.7 ± 27.2	2.3 ± 0.1
Period IV	Apr.08 – Oct.08 / 189 days	394.0 ± 16.2	815.5 ± 48.9	2.1 ± 0.2
Period V	Oct.08 – Oct.09 / 364 days	342.1 ± 9.9	548.1 ± 16.1	1.6 ± 0.1
Period VI	Oct.09 – Sep.10 / 349 days	281.0 ± 27.8	467.1 ± 48.2	1.7 ± 0.2
Period VII	Sep.10 – Sep.12 / 699 days	365.6 ± 36.3	674.3 ± 68.6	1.8 ± 0.3

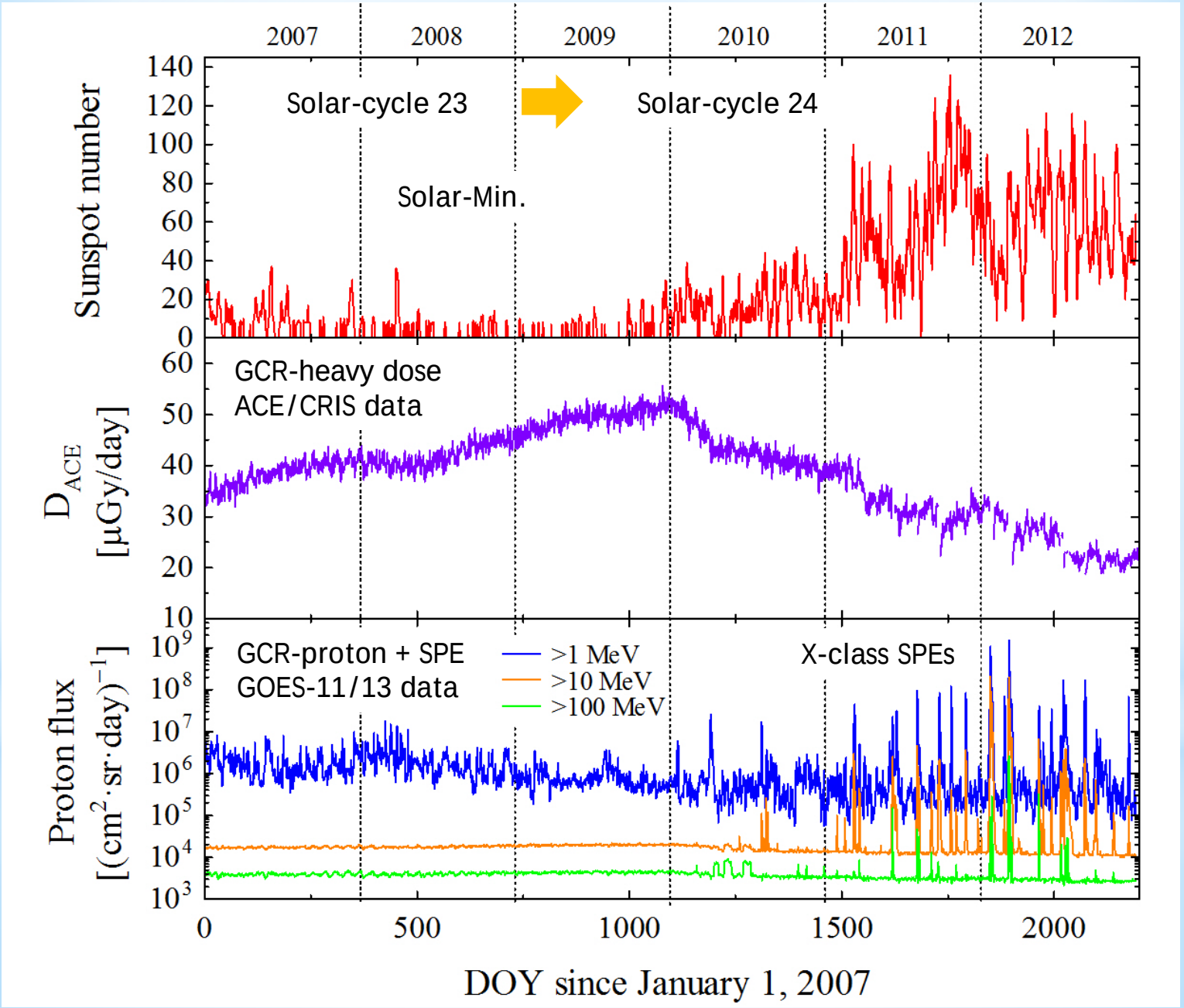
* Total dose rate variations in 2007 - 2012 *



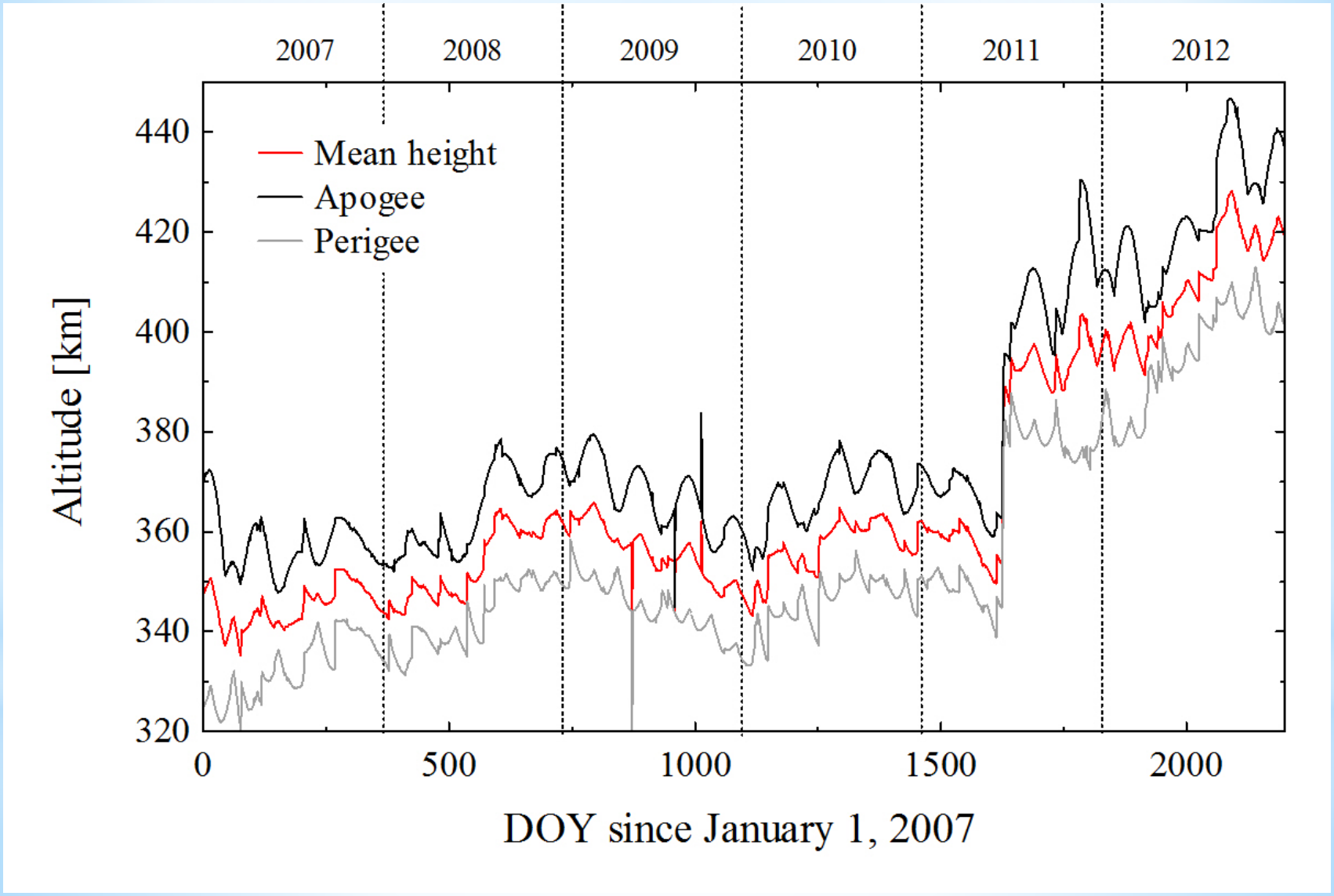
* Dose variations of high LET component *



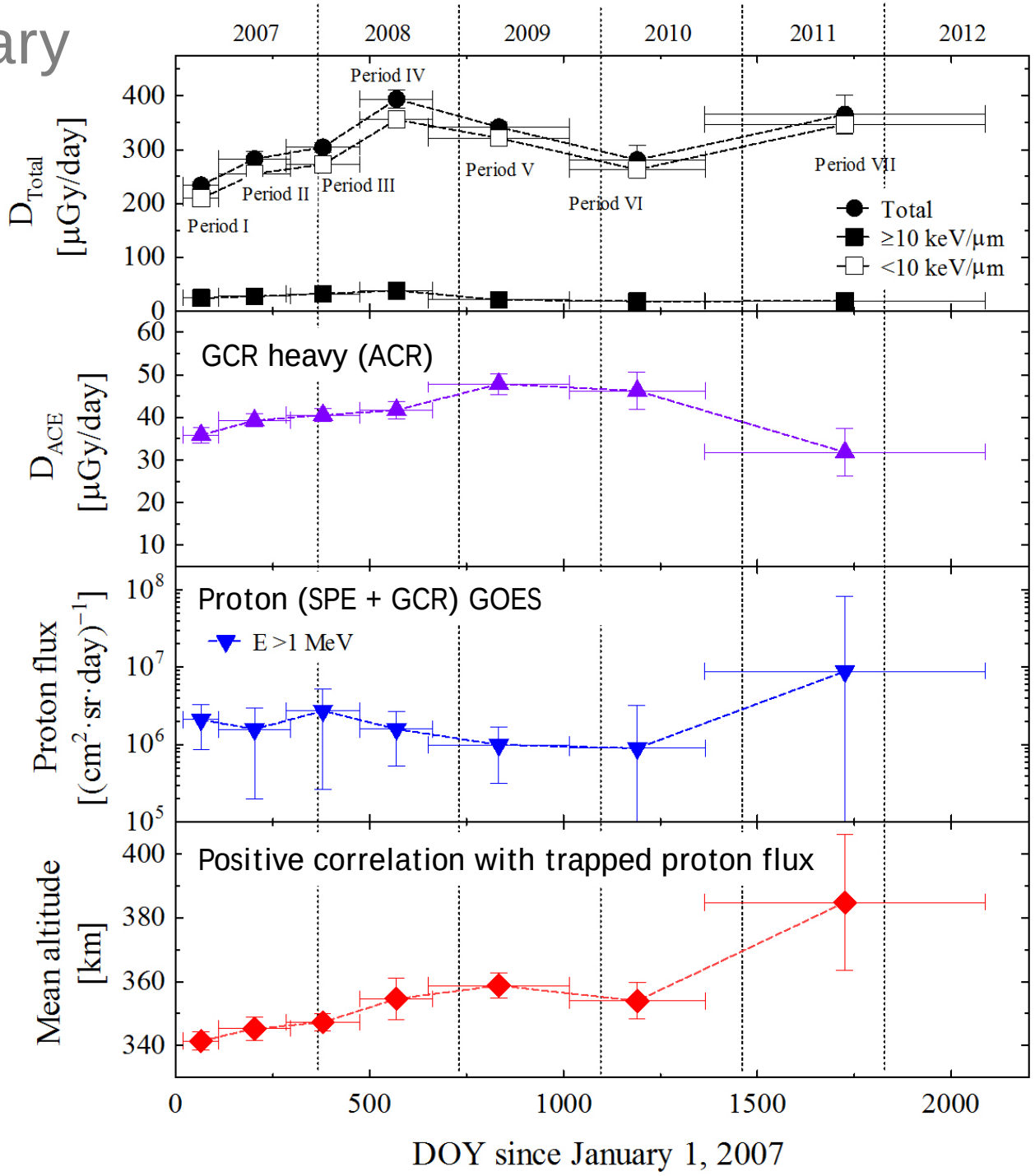
* Solar activity parameters *



* ISS Orbital parameters *



Preliminary



* Summary *

- Long-term dose variations between 2007 and 2012 have been observed with passive dosimeters in the ISS Piers-module

- Dose rate increased from 2007 to 2008 in solar quiet period (no SPE events)
  - Incremental increase in the altitude of the ISS induced the increase of trapped proton flux encountered during passage of the ISS through the SAA

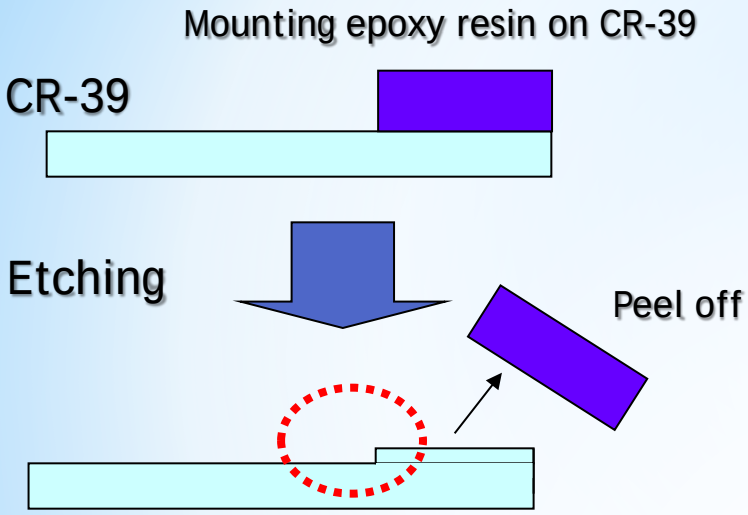
- Dose rate decease from 2008 to 2010
  - It seems to be due to the decrease of proton flux according to GOES data (geostationary orbit)

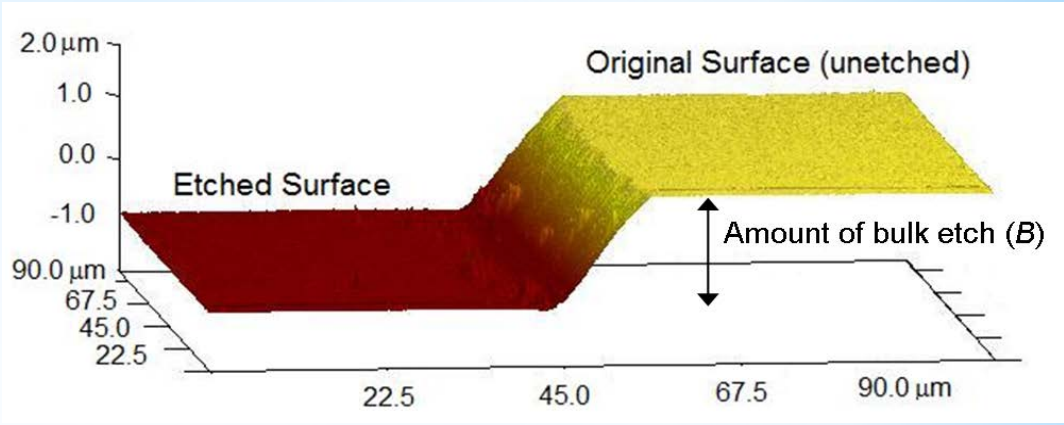
- $<Q_{Total}>$ dropped to be 1.6 in 2009-2010, while $<Q_{LET \geq 10keV/\mu m})$ kept ~12.0
  - It impliesthat the trapped proton flux increases with the ISS altitude increase

- Dose rate increased again in 2011-2012 and also $<Q_{LET \geq 10keV/\mu m})$ raised to be ~18.0
  - It implies that SPE & trapped proton flux increases so much as well as the proton-induced heavy recoils

*Back up slides *

* Bulk etch (B) measurement *

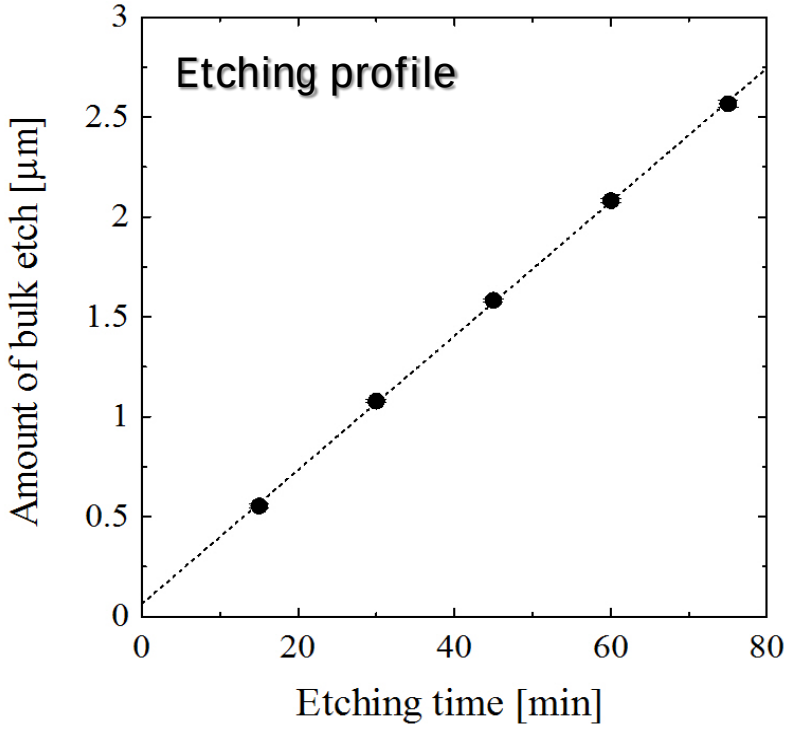




A step is appeared between un-etched surface (with mask) and etched one

→ Step height corresponds to amount of bulk etch (B)

N. Yasuda et al., (1996)

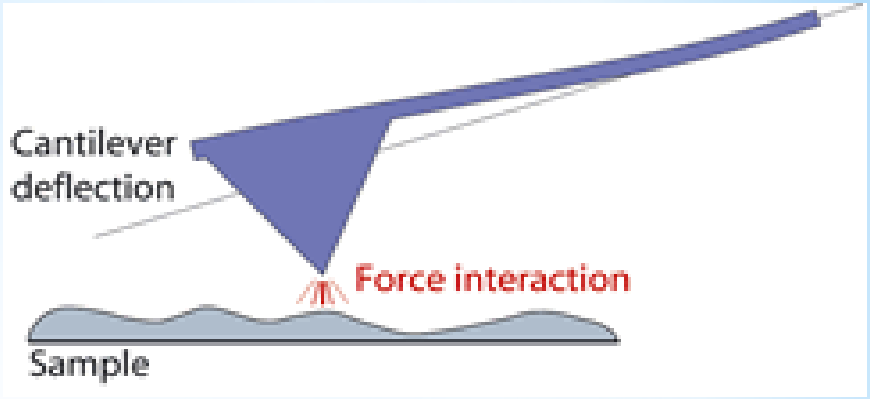


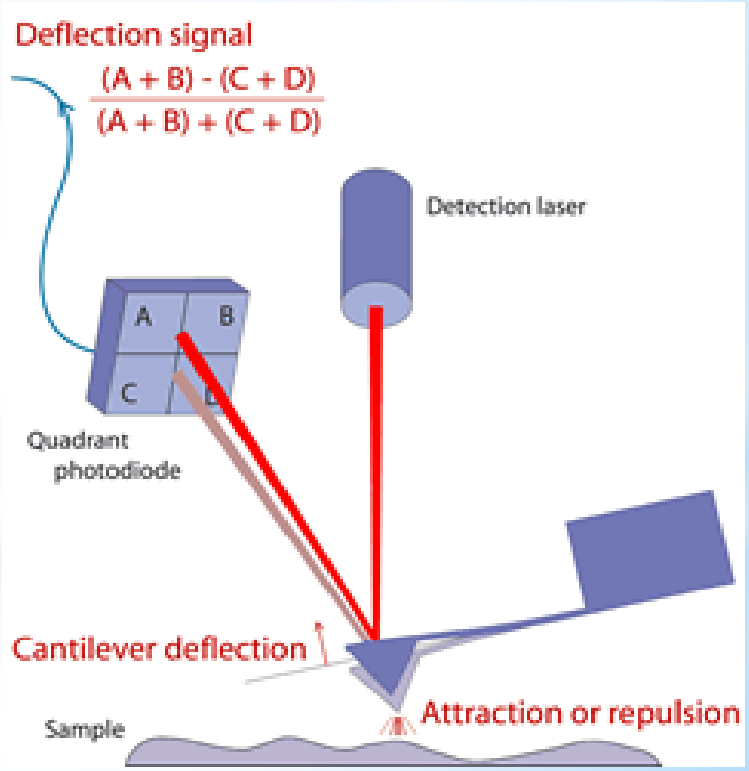
○ Etching condition

- 7N NaOH 70ºC

* Atomic Force Microscope Analysis of CR-39 *

* Tapping mode (or Contact mode)
* The cantilever is vibrated at its resonant frequency (~200-400 kHz)
* As the tip is scanned across the surface its vibration amplitude is affected by interactions with the surface
* AFM system include feedback to adjust the height of the cantilever for surface tracking by a laser
* The AFM records surface height, *Z*, with respect to *X* and *Y*
* AFM data is a topographic map of the scanned surface



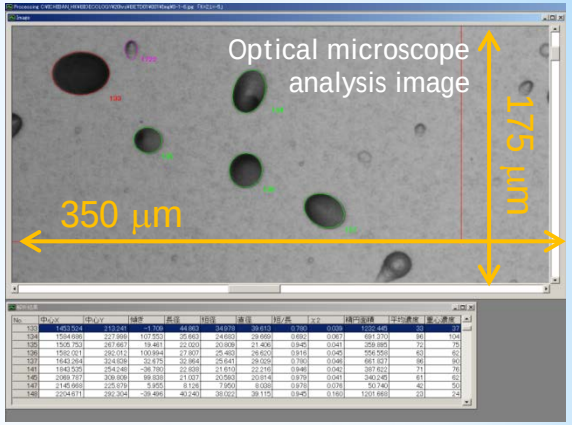


From JPK Instruments web site
http://japan.jpk.com/what-is-atomic-force-microscopy.432.ja.html

* Special analysis of CR-39 *

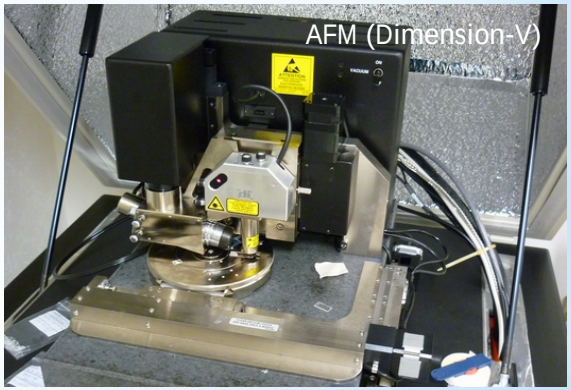
Optical microscope analysis (conventional):

- CR-39 plates for Session#1~#5 (0.5 ~1 yr exposure) have been etched 8 hrs in 7N NaOH 70 °C
- Mean bulk etch was 14.3 μm
- Scanned image area: 4 mm^2 (0.35 μm/pix resolution)
- Analyzed with HSP-100 and PitFit software



Atomic force microscope analysis for long exposure samples:

- CR-39 plates for Session#6 and #7 (2 and 5.5 yr exposures) have been etched 0.5 hrs in 7N NaOH 70 °C
- Mean bulk etch was 1.056 μm
- Analyzed with AFM (Veeco/Demension-V) and PitFit



[Cantilever]
125μm length / Tip 10μm length
Resonance freq. ~300 kHz / Spring const. ~40 N/m

[Scanning]
- Mode and scan rate : Tapping / 1.5 Hz
- Image size: 25μm × 25μm
- Resolution: 1024pix × 1024pix (i.e. 24 nm/pix resolution)
- Scanned image area:
  1.0 mm^2 (1588 images) for Session#6 (2 yr)
  0.6 mm^2 (946 images) for Session#7 (5.5 yr)