RADIOISOTOPES, **68**, 411–418 (2019)
doi: 10.3769/radioisotopes.68.411

Special Issue

Applications of Charged Particle Accelerators—Impact of the NIRS-HIMAC Facility—
Section 5 【Space Science】Space Radiation Physics and Biology

5.2.2 Intercomparison of Radiation Detectors and Dosimeters for Use in Manned Space Flight

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The ICCHIBAN project was an international collaboration to intercalibrate and intercompare the response of the different detectors and instruments used for radiation dosimetry aboard manned spacecraft. The objectives of the ICCHIBAN project were: 1) to determine the response of space radiation instruments and dosimeters to heavy ions of charge and energy similar to that found in the galactic cosmic radiation (GCR) spectrum; 2) to compare the response and sensitivity of various space radiation monitoring instruments and aid in reconciling differences in measurements made by various radiation instruments during space flight; and 3) to establish and characterize a heavy ion "reference standard" against which space radiation instruments can be calibrated. ICCHIBAN experiments were carried out at a number of particle accelerator facilities, the vast majority, eight, using the HIMAC heavy ion accelerator at the National Institute for Radiological Sciences, Chiba, Japan. Benefits of the ICCHIBAN project included the identification and correction of problems in calibration and data interpretation of a number of active space radiation instruments, and the demonstration of the overall efficacy and reproducibility of passive radiation dosimeters, especially luminescence-based detectors such as TLD and OSLD used in conjunction with CR-39 PNTD.

Key Words: HIMAC (Heavy Ion Medical Accelerator in Chiba), ICCHIBAN project (InterComparison for Cosmic-ray with Heavy Ion Beams At NIRS), inter-comparison, detector calibration

1. Introduction

One of the more unique scientific programs carried out at HIMAC (Heavy Ion Medical Accelerator in Chiba) was the ICCHIBAN project: the Inter-Comparison of Cosmic Rays with Heavy Ion Beams At NIRS. ICCHIBAN consisted of a multi-year program of experiments to expose dosimeters and radiation detectors as part of the space radiation protection programs of the Japan Aerospace Exploration Agency (JAXA), the Russian Space Agency (RSA), the European Space Agency (ESA), and the National

Aeronautics and Space Administration (NASA). Researchers from all over the world using and/or developing space radiation dosimeters and detectors were invited to come to HIMAC with their detectors or to send their detectors to HIMAC for exposure as part of a campaign to inter-calibrate, characterize and better understand how these detectors operated in the space radiation environment and how best to compare results obtained during spaceflight by these different detectors.

ICCHIBAN was conceived following the fourth Workshop on Radiation Monitoring for the International Space Station (WRMISS http://www.wrmiss.org) meeting in 1999 at Farnborough, UK, when it was realized that there were significant discrepancies in the results from space radiation detectors and dosimeters used by various laboratories throughout the world and that a good way to investigate and resolve these discrepancies would be to carry out controlled experiments with these detectors using well-characterized heavy ion beams at ground-based particle accelerator facilities. The HIMAC at NIRS (National Institute of Radiological Sciences), Chiba Japan, was identified as being ideally suited for this purpose, being capable of accelerating heavy ions prominent in the GCR spectrum to energies com-

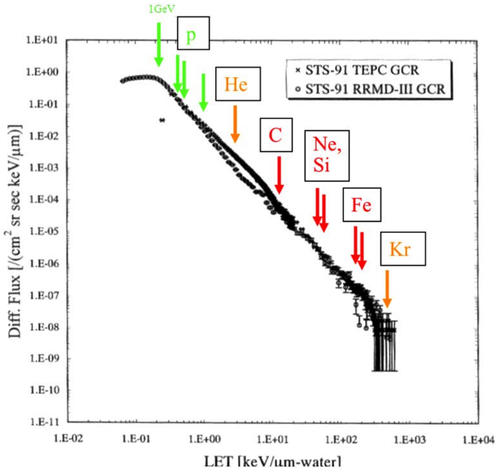

Fig. 1 Representative LET spectra from space as measured aboard the STS-91 Space Shuttle mission [Doke 2001], showing where heavy ion beams available at HIMAC fall in the spectrum (Color online).

Table 1 Details of the ICCHIBAN experiments carried out using the HIMAC.ICCHIBAN Experiment

	Dates	Heavy Ion Beams
1 (active detectors)	11-13 Feb 2002	400 MeV/nucleonucleon C, 400 MeV/nucleon Fe
2 (passive detectors)	23-28 May 2002	150 MeV/nucleon He, 400 MeV/nucleon C 490 MeV/nucleon Si, 500 MeV/nucleon Fe
3 (active detectors)	3-6 Feb 2003	800 MeV/nucleon Si, 500 MeV/nucleon Fe
4 (passive detectors)	19-30 May 2003	150 MeV/nucleon He, 400 MeV/nucleon C 400 MeV/nucleon Ne, 500 MeV/nucleon Fe
5 (active detectors)	14-17 Feb 2004	150 MeV/nucleon He
6 (passive detectors)	4-15 June 2004	135 MeV/nucleon C, 500 MeV/nucleon Ar, 400 MeV/nucleon Kr
7 (active detectors)	13-17 Sept 2005	150 MeV/nucleon He, 400 MeV/nucleon C, 500 MeV/nucleon Ar, 200 MeV/nucleon Fe
8 (passive detectors)	13-17 Sept 2005	150 MeV/nucleon He, 400 MeV/nucleon C, 400 MeV/nucleon O, 200 MeV/nucleon Fe

monly encountered in the space radiation environment. Fig. 1 shows the LET spectra measured by two instruments aboard the STS-91 Space Shuttle mission,[1] together with heavy ion beams available at HIMAC demonstrating the suitability of HIMAC in simulating exposure to portions of the space radiation environment.

A total of eight ICCHIBAN experiments were carried out at HIMAC between 2002 and 2005, details of which are listed in Table 1. Additionally several other ICCHIBAN experiments were carried out at other ground-based accelerators including the NIRS cyclotron and later a series of three Space Intercomparison (SI) ICCHIBAN experiments were carried out aboard the International Space Station (ISS). Early on it was realized by the ICCHIBAN organizers that the conditions for exposing active detectors (detectors requiring power and capable of generating time resolved data) were significantly different from those for passive detectors (*e.g.* thermoluminescence detectors (TLD) and CR-39 plastic nuclear track etch detectors (PNTD) requiring no power, but a post-exposure readout). As a result odd-numbered ICCHIBAN experiments were devoted to active detectors, while even-numbered ICCHIBAN experiments were dedicated to passive detectors.

2. ICCHIBAN Experiments for Active Detectors

Most of the instruments used in the four ICCHIBAN experiments dedicated to active detectors are listed in Table 2. Details regarding each of these instruments can be found in the two NIRS HIMAC reports devoted to ICCHIBAN project results.[2, 3] Representative results from the intercomparison of active detectors at HIMAC during the ICCHIBAN program, in particular those from the ICCHIBAN-3 experiment, are illustrated and discussed below.

An example of the type of intercomparison made between different active space radiation detectors can be seen in Fig. 2. Fig. 2 shows an intercomparson of LET spectrum, as measured in Si telescopes, and lineal energy (y) spectrum as measured in TEPCs for exposures made to a beam of 500 MeV/nucleon Fe in the physics (PH2) beam of HIMAC. Direct comparison of values obtained by different active detectors were difficult, due to the fact that different instruments often measured different physical quantities and had different maximum and minimum LET thresholds. For example, the JSC TEPCs measure lineal energy distribution, y, in a tissue equivalent gas, while silicon detectors measure linear energy transfer (LET) distributions in silicon. For purposes

Table 2 Detectors/Instruments exposed during the active ICCHIBAN experiments

Institution	Instrument Name	Detector Type
	Active Detectors	
Kiel Univ.	DOSTEL -2	Silicon Telescope
	DOSTEL-D	Silicon Telescope
NASA-JSC	IV-CPDS	Silicon Telescope
	ISS-TEPC	Tissue Equivalent Proportional Counter
	Shuttle-TEPC	Tissue Equivalent Proportional Counter
NIRS	Liulin-4J	Silicon
Waseda Univ.	RRMD-III	Silicon Telescope
	Reference Detectors	
LBNL	Ground Based Reference Detectors	Silicon Stack + ToF Scintillator
NIRS	Position Sensitive Silicon Detector	Double Strip Silicon Detector

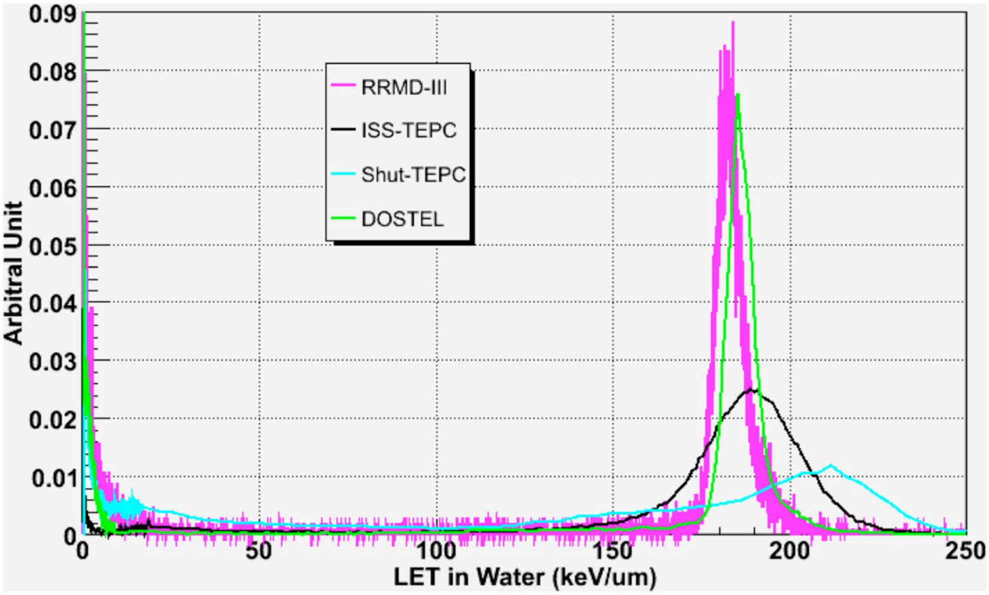

Fig. 2 LET distribution of measured in the 500 MeV/nucleon Iron beam. The instruments were exposed at normal incidence (0°) to the beam (Color online).

Table 3 Results from 500 MeV/nucleon ^{56}Fe irradiations during the ICCHIBAN-3 experiment, for irradiation at normal incidence at the center of the detectors. (0°, without absorber) (N.R. means 'Not Reported.') DOSTEL-2(Avg.) was obtained from events which are in a LET range 164–220 keV/μm)

	LET or y_f(y_d) (keV/ m- H_2O)	Quality Factor (ICRP-60)	Absorbed Dose (nGy/ particle)	Dose Equivalent (nSv/ particle)
RRMD-III(Old)	188	21.9	62.8	1370
RRMD-III(New)	184	22.1	61.3	1360
DOSTEL-2(Avg.)	202.2	21.1	N.R.	N.R.
DOSTEL-2(Peak)	187	-----	N.R.	N.R.
ISS-TEPC	174.98 (190.08)	16.99	202.25	4161.48
Shuttle-TEPC	134.7 (185.4)	22.0	N.R.	N.R.
Calculation	187.8	21.89	300.9	6587

of comparison an assumption was made that the average y distribution corresponded to the average LET distribution. Measurements obtained from different instruments also generally have different systematic and statistical errors. Nevertheless, one can see broad agreement between the four different instruments. Measurements are not shown for the Liulin Si detector since it's maximum LET threshold lies below the LET value of the Fe beam. The broad peaks seen in the TEPC spectra are due to the chord length distribution in these cylindrical or spherical detectors, while the sharper peaks seen for the Si telescope are, of course, the result of a single, well-characterized chord length through these detectors. Table 3 shows the dosimetric values measured for the 500 MeV/nucleon Fe beam, together with theoretical calculations.

Exposures to the 400 MeV/nucleon ^{20}Ne beam during the ICCHIBAN-4 experiment were carried out in the HIMAC Biology (HIMAC BIO) exposure

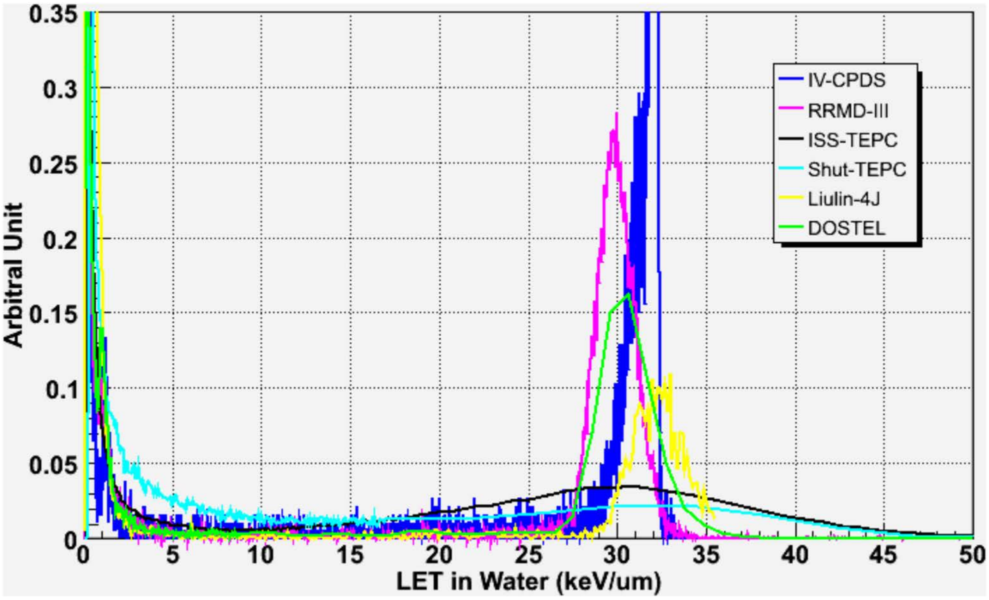

Fig. 3 Measured LET distributions for the 400 MeV/nucleon ^{20}Ne beam in the BIO exposure room during the ICCHIBAN-4 experiment. The instruments were exposed at normal incidence (0°) relative to the beam (Color online).

Table 4 Results from the 400 MeV/nucleon ^{20}Ne irradiations in the HIMAC BIO exposure room during the ICCHIBAN-3 experiment. Irradiation at normal incidence at the center of the detectors (0°, without absorber). N.R. means 'Not Reported.' DOSTEL-2(Avg.) was obtained from events which between 26 and 35 keV/μm

	LET or y_f (y_d) (keV/um-H_2O)	Quality Factor (ICRP-60)	Absorbed Dose (nGy/ particle)	Dose Equivalent (nSv/ particle)
RRMD-III(Old)	29.4	7.22	9.82	70.9
RRMD-III(New)	29.9	7.37	9.97	73.5
DOSTEL-2(Avg.)	33.4	8.7	N.R.	N.R.
DOSTEL-2(Peak)	30	-----	N.R.	N.R.
ISS-TEPC	22.43 (41.89)	8.78	1.35	14.04
Shuttle-TEPC	15.5 (28.6)	6.9		
Liulin-4J	32.2	(8.1)	N.R.	N.R.
Calculation	31.40	7.85	50.3	395

room. By irradiating the detectors in the BIO room it was possible to obtain a wide, uniform beam that covered the entire sensitive volume of each detector. Fig. 3 shows the LET distributions measured by the instruments exposed to the 400 MeV/nucleon neon beam at an incident angle of 0° with no absorber. The dosimetric values for this configuration are shown in Table 4. Because of the relatively low LET of the primary ions in the neon beam, it was possible to obtain LET distributions with the Liulin-4J MDU and JSC IV-CPDS instruments.

In general, those instruments based on silicon detectors generally showed good agreement with one another and with model calculations. The ISS-TEPC had a very different response, but we believe this to be due in large part to the different operating principles of this type of detector. Each instrument has its advantages and disadvantages. For example, a TEPC type detector has a significant advantage in the complex radiation field encountered in space, because it can measure the energy deposition to biological tissue. As mentioned above, this is only a small sample of all the intercomparisons made with active detectors during the ICCHIBAN program. In addition, ICCHIBAN provided the first opportunity for a number of active detectors to be characterized at a ground-based heavy ion accelerator facility. This opportunity revealed not only some problems and limitations of instrument hardware, but also in the software used in recording and analyzing the data.

3. ICCHIBAN Experiments for Passive Detectors

ICCHIBAN experiments for passive detectors (even numbered ICCHIBAN experiments) were

Table 5a TLD and OSLD dose results for the ICCHIBAN-4 Blind #4 Exposure

Laboratory	Detector	Dose (mGy)	Percentage Difference
Nominal		12.51	
ATI (Austria)	TLD-600 (^6LiF:Mg,Ti)	11.28 ± 0.22	9.8
	TLD-700 (^7LiF:Mg,Ti)	11.91 ± 0.22	4.8
ERI (USA)	TLD-700 (^7LiF:Mg,Ti)	12.95 ± 0.47	3.5
IMBP (Russia)	LiF:Mg,Ti	10.36 ± 0.33	17.2
IFJ (Poland)	MTS-7 (^7LiF:Mg,Ti)	12.50 ± 0.26	0.1
	MTT-7 (^7LiF:Mg,Ti)	12.64 ± 0.51	1.0
	MCP-7 (^7LiF:Mg,Cu,P)	11.91 ± 0.10	4.8
JAXA (Japan)	MSO (Mg_2SiO_4:Tb)	12.60 ± 0.49	0.7
JSC (USA)	TLD-100 (LiF:Mg,Ti)	10.85	13.3
	TLD-700 (^7LiF:Mg,Ti)	10.70	14.5
	TLD-600 (^6LiF:Mg,Ti)	10.65	14.9
	TLD-300 (CaF_2:Tm)	9.18	26.6
KFKI (Hungary)	$CaSO_4$:Dy	12.10 ± 0.12	3.3
NPI (Czech Rep.)	Al-P Glass	12.40	0.9
	Al_2O_3:C	10.50	16.1
OSU (USA)	OSL Chips, Integral (Al_2O_3:C)	12.10 ± 0.10	3.3
	OSL Chips I_0 (Al_2O_3:C)	13.00 ± 0.20	3.9
	Luxel OSL (Al_2O_3:C)	13.40 ± 0.00	7.1
	Luxel OSL I_0 (Al_2O_3:C)	14.70 ± 0.10	17.5
	TLD-100 Peak Height (LiF:Mg,Ti)	11.10 ± 0.47	11.3
	TLD-100, Area HT (LiF:Mg,Ti)	12.50 ± 0.50	0.1

Table 5b TLD and OSLD dose results (efficiency correction) for the ICCHIBAN-4 Blind #4 Exposure

Laboratory	Detector	Dose (mGy)	Percentage Difference
Nominal		12.51	
NPI (Czech Rep.)	Al-P Glass	12.70	1.5
	Al_2O_3:C	12.10	3.3
OSU (USA)	OSL Chips, Integral (Al_2O_3:C)	12.50 ± 0.20	0.1
	OSL Chips I_0 (Al_2O_3:C)	12.40 ± 0.20	0.9
	Luxel OSL (Al_2O_3:C)	12.60 ± 0.10	0.7
	Luxel OSL I_0 (Al_2O_3:C)	12.80 ± 0.20	2.3

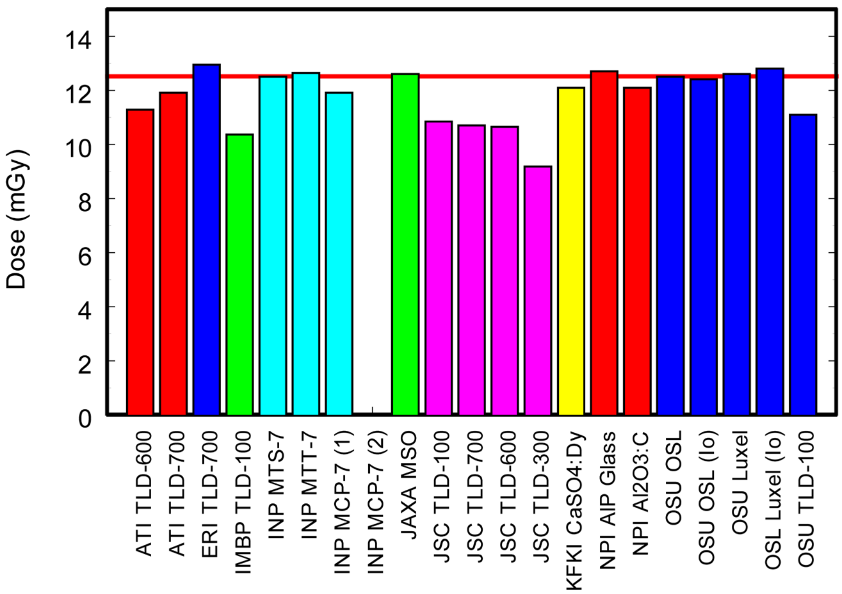

Fig. 4 Doses measured in TLD and OSLD for the ICCHIBAN-4 Blind #4 exposure designed to simulate an actual space radiation exposure in LEO (Color online).

carried out in the HIMAC BIO room in order to take advantage of the large beam size (∼10 cm diameter) and the consequent ability to irradiate multiple passive detectors in the beam during a single exposure. In general, there were two types of passive detector irradiation. For known exposures, participants were told the ion species, energy, LET and fluence of the exposure. For blind exposures, this information was withheld from the participants. Known exposures were largely carried out for purposes of detector calibration, while blind exposures, often consisting of irradiations to multiple heavy ion beams, were carried to simulate actual space radiation exposures. To illustrate the ICCHIBAN experiments for passive detectors, results from one of the blind exposures carried out as part of the ICCHIBAN-4 experiment are described. For these exposures, detectors were provided by nine different laboratories. Most laboratories provided only TLDs, but several laboratories also provided CR-39 PNTD and one laboratory used both TLD and optically stimulated luminescence detectors (OSLD).

The ICCHIBAN-4 Blind #4 exposure was designed to simulate an actual exposure to the space radiation environment in low-Earth orbit to the degree possible given the limitations of the available resources. Each Blind #4 dosimeter package was exposed to 11.1 mGy of ^{60}Co γ-rays and 1 mGy of 150 MeV/nucleon ^{4}He ions to simulate the low-LET component of the LEO space radiation environment, and to 1000 particles/cm^2 each of 400 MeV/nucleon ^{12}C, 400 MeV/nucleon ^{20}Ne, and 500 MeV/nucleon ^{56}Fe ions to simulate the HZE particle component. Agreement amongst results from the TLD and OSLD measurements, shown in Tables 5a and 5b, and in Fig. 4, in most cases fell within 10% of the nominal dose value of 12.51 mGy. Because the low-LET component was so much larger than the HZE particle component, little if any effect of the reduced dose registration efficiency phenomenon from high-LET particles could be seen. As a consequence of the dominance of the low-LET component, several laboratories that would ordinarily correct their doses due to the high-LET dose registration efficiency phenomenon (*e.g*. ATI, IFJ) did not make a correction for the Blind #4 exposure. This is a noteworthy observation given the fact that the Blind #4 exposure was designed to be a realistic simulation of a LEO space radiation exposure—although under the constraint that the dominant proton component was simulated using ^{60}Co γ-rays. It implies that while methods exist that improve the accuracy of TLD/OSLD measurements in radiation fields dominated by high-LET particles, their application to "mixed" radiation fields dominated by low-LET radiation can be quite complicated and always has to be taken as "best effort" method. As is the case for the active instruments, this single result from the ICCHIBAN-4 experiment is representative of the many known and blind experiments for passive dosimeters carried out with the auspices of the ICCHIBAN program.

4. Conclusion

The ICCHIBAN experiments carried out at HIMAC demonstrated that, with a minimum of funding and without official sanction from ESA, JAXA, NASA, or RSA, an international collaboration for the intercomparison and intercalibration of space radiation instrumentation can be successfully realized. For this success, the ICCHIBAN organizers and participants give great thanks to the NIRS HIMAC Program Advisory Committee for recognizing the importance of the ICCHIBAN project to international space radiation protection efforts and providing the necessary machine time. The ICCHIBAN organizers and participants also thank the staff of HIMAC for the smooth and flawless operation of the accelerator during the performance of these unique experiments.

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