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

## 5.2.5 Calibration of Detectors that Have Flown on Mir, ISS, Lunar Reconnaissance Orbiter, the Orion Spacecraft and the Mars Science Laboratory

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*A variety of radiation detectors and instruments have been deployed to characterize the radiation environment in low and high Earth orbit, lunar orbit, Mars orbit and on the surface of Mars. Here we discuss the testing and calibration of these detectors using HIMAC ion beams.*

Key Words: HIMAC (Heavy Ion Medical Accelerator in Chiba), space radiation detector, ICCHIBAN project (InterComparison for Cosmic-ray with Heavy Ion Beams At NIRS), radiation protection, calibration by accelerator beam

### 1. Introduction

Since HIMAC (Heavy Ion Medical Accelerator in Chiba) was opened to the international research community twenty years ago, a large number of researchers specializing in space radiation physics and biology from all over the world have carried out experiments using HIMAC's heavy ion beams. One of the most important areas is in the calibration of radiation detectors used for space crew dosimetry and

for characterization of the space radiation environment so that today, HIMAC is the premier heavy ion calibration facility for space radiation instruments in the world. HIMAC is able to provide a wide range heavy ion beams relevant to space including protons, helium, carbon, nitrogen, oxygen, neon, silicon, argon, titanium, iron, krypton and xenon with energies for 100 to 500 MeV/n. This range of ion/energy combinations covers nearly all the relevant particle species and energies of concern to the radiation pro-

tection of space crews. Heavy ions such as iron are biologically important because, while relatively rare in the galactic cosmic radiation (GCR) spectrum, they are very highly ionizing and possess correspondingly high quality factors.

Researchers from many space agencies, universities, institutions and industry in many countries have used HIMAC heavy ion beams over the past 25 years. They include JAXA (Japan Aerospace Exploration Agency), and Waseda, Tokyo and Tohoku Universities in Japan, NASA (National Aeronautics and Space Administration), LBNL (Lawrence Berkeley National Laboratory), the University of Houston, the University of Tennessee and Oklahoma State University, and SwRI (Southwest Research Institute) in the USA, DLR (German Aerospace Center), CAU (Christian Albrechts University), and GSI (Helmholtz Centre for Heavy Ion Research) in Germany, IBMP (Institute of Biomedical Problems) and Energia (S.P. Korolev Rocket and Space Corporation) in Russia, HPI (Health Protection Agency) in UK, STIL (Solar Terrestrial Influences Laboratory) in Bulgaria, NPI (Nuclear Physics Institute) in Czech Republic, MTA-EK (Centre for Energy Research) in Hungary, and the IFJ-PAN (Institute of Nuclear Physics) in Poland among others.

To cite a number of examples, JAXA developed their personal and area dosimeter package, PADLES (Passive Dosimeter for Lifescience Experiments in Space) which is combination of CR-39 plastic nuclear track detectors (PNTDs) and thermoluminescence dosimeters (TLD) and was calibrated in HIMAC. In particular an important calibration curve for CR-39 PNTD was obtained using various LET heavy ion beams.<sup>1)</sup> In addition, an automatic optical telescope was developed in NIRS (National Institute of Radiological Sciences). The PADLES has several variants for different applications, such as Crew PADLES, Area PADLES, Bio PADLES and Dosimetric PADLES, all utilized in the International

Space Station (ISS). Other JAXA space radiation measurement instruments developed using HIMAC beams include RRMD-III (Real-time Radiation Monitoring Device)<sup>2)</sup> and PS-TEPC (Position Sensitive Tissue Equivalent Proportional Chamber) using HIMAC beams.<sup>3)</sup>

NASA and collaborating universities and companies have developed various detectors and personal monitors discussed elsewhere in this section, including MSL-RAD on the Curiosity Mars rover,<sup>4,5)</sup> the Radiation Environment Monitor (REM) with Timepix technology<sup>6)</sup> and ATED (Active Tissue Equivalent Dosimeter).

IBMP and collaboration researchers from the Eastern European countries have developed active detectors such as DB-8, M-16 and Liulin,<sup>7)</sup> as well as various passive dosimeters. These detectors and dosimeters have been used in space for many years but were originally only calibrated using radioactive sources. Heavy ion beams at HIMAC made possible calibration using simulated GCR of relevant particle type and energy.

The German Aerospace Center (DLR) Institute of Aerospace Medicine has developed and tested various passive and active detector systems used currently onboard the ISS, as well as on several research satellites. One example are the thermoluminescence detectors applied used for personal dosimetry<sup>8)</sup> and area monitoring<sup>9)</sup> described below. These dosimeters were extensively calibrated at HIMAC.<sup>7,9)</sup>

Collaborations at HIMAC have stimulated collaboration in space experiments. A major achievement was the MATROSHKA project in which a human phantom torso instrumented with a number of passive and active detectors was located both outside and inside the ISS. Radiation dose distributions in the phantom by various space radiation (heavy ions, light ions, protons and neutrons) were measured *in situ*.<sup>10, 11)</sup> In the DOSIS & DOSIS 3D projects, organized by DLR, passive dosimeter packages by

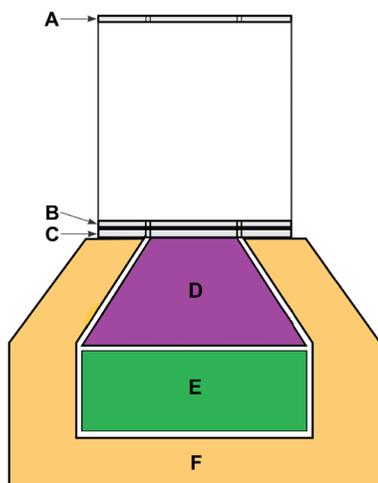


Fig. 1 Schematic of the MSL-RAD detector (Color online).

international collaborators were installed in the ESA Columbus module<sup>9)</sup> along with active radiation detectors calibrated at HIMAC.<sup>12)</sup>

Many of the physics researchers who participated in the ICCHIBAN intercomparison campaign reviewed in section 5.2.2 had their own experiments in HIMAC in addition to ICCHIBAN.<sup>13)</sup> HIMAC is a favored venue for research due to its wide range of GCR-like beams, due to its stable operation, excellent support staff and facilities and generous beam time.

Some of the active and passive radiation detectors calibrated and characterized at HIMAC are described below. As pointed out above, this should by no means be considered an exhaustive list.

## 2. Active Space Radiation Detectors

### 2.1 Mars Science Laboratory Radiation Assessment Detector (MSL-RAD)

The MSL-RAD detector, part of the science payload aboard the Curiosity rover on Mars, consists of an electronics box mated to the RAD Sensor Head (RSH). The RSH is pictured schematically in Fig. 1; it consists of three silicon detectors (A, B, and C), a thallium-doped CsI scintillator (D), and two plastic

scintillators (E and F). The detectors are arranged so that the D and E detectors record neutral particles ( $\gamma$ -rays and neutrons) with the C and F detectors acting as veto detectors to reject charged particles. Detailed descriptions can be found in the literature.<sup>14, 15)</sup>

Two nearly identical RAD units were built, a flight model (FM) that has been operating on Mars since 2012, and an engineering model (EM). The EM was used at HIMAC and other accelerator facilities to measure the response of the detectors to a variety of beam ions and energies. A primary concern is the response of the scintillators to highly ionizing particles, such as low-energy protons and more energetic heavy ions. In particular, the D detector is used for particle identification and, in the case of stopping particles, total energy measurements, and the E detector is used for dosimetry. The complexity of the response can, to some extent, be mapped using beam data. Because the response is not a constant, but rather is a function of the charge and mass of the incident particle, in principle data are needed for all ions that are to be measured, which in the case of the galactic cosmic rays, means all ions from charge 1 to at least 26. Given limited beam hours and the fact that not all ion species are available to be accelerated, one way to obtain data on many species at the same time is to use a heavy beam such as  $^{56}\text{Fe}$  with a low-Z target to produce projectile fragments with narrow velocity distributions. An example of the data obtained is shown in Fig. 2, where the apparent energy deposited in the D detector (CsI) is plotted against the energy deposited in the A and B silicon detectors for a 500 MeV/nucleon  $^{56}\text{Fe}$  beam incident on  $2.9\text{ g cm}^{-2}$  of  $\text{CH}_2$ . The most heavily populated cluster is due to surviving iron ions; other clusters are visible for charges as low as 15 or 16. The black dots are the average energy deposits in D for a given species as predicted by the PHITS Monte Carlo, for particles that stop in D. The gaps between the measured and predicted points indicate that the

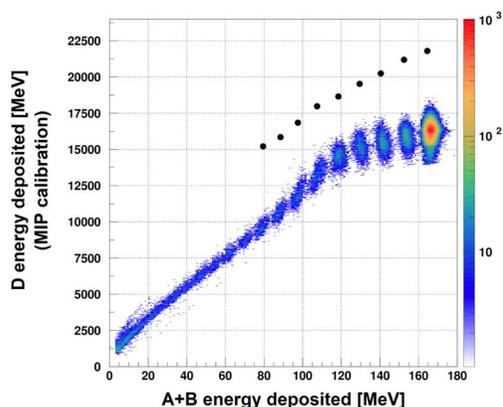


Fig. 2 Energy deposited in the MSL-RAD D detector (CsI) plotted against the energy deposited in the A and B silicon detectors for a 500 MeV/nucleon  $^{56}\text{Fe}$  beam incident on  $2.9 \text{ g cm}^{-2}$  of  $\text{CH}_2$  (Color online).

quenching of signals from high-energy heavy ions is on the order of 30–50% and does not appear to obey a simple scaling relationship with the energy deposited.

In 2014 RAD was tested on the HIMAC experimental biology beamline using the 290 MeV/nucleon  $^{12}\text{C}$  beam. The goal of this test was to better understand the dose calibration of the RAD B and E detectors, which are used for dosimetry. In the flight environment, it is found that the dose rate in E is roughly 40–45% larger than that in B, most of which is due to the difference in ionization potentials between silicon (B) and plastic (E). However with the relatively low-energy beam, it was found that the E dose rate was lower than the B dose rate, likely due to the much higher particle energies (typically  $\sim 1 \text{ GeV/nucleon}$ ) in the flight environment.

## 2.2 Cosmic Ray Telescope for the Effects of Radiation (CRaTER)

The CRaTER instrument<sup>16)</sup> is a particle telescope that has been making measurements in lunar orbit since 2009. It is part of the Lunar Reconnaissance Orbiter instrument payload. CRaTER's unique design, shown in Fig. 3, allows important tests of

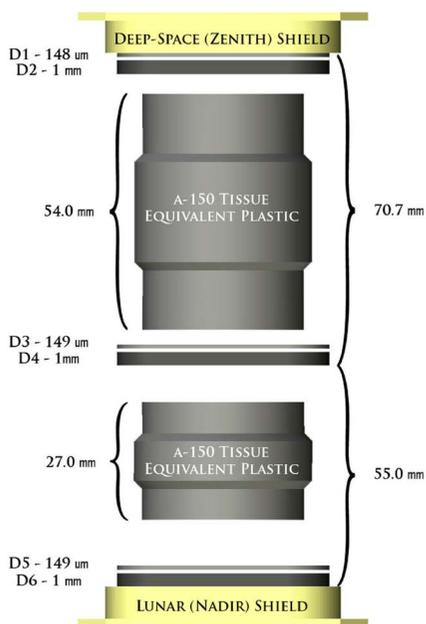


Fig. 3 Schematic of the CRaTER detector (Color online).

shielding of both galactic cosmic rays and solar energetic particles by tissue-equivalent plastic. The geometry used to accomplish this has some unintended consequences which complicate the data analysis. “Out of cone” particles have trajectories that are outside the nominal acceptance of the detector, but create secondary particles—either through fragmentation in the plastic or by production of high-energy delta electrons—that are in the acceptance, resulting in coincidence events in which different detectors measured different particles. To study these effects in detail, in 2012 the CRaTER flight spare unit was brought to HIMAC along with a precision rotation stage, and was placed in the PH2 physics beamline. Four beams were used in this test: protons at 160 MeV,  $^4\text{He}$  at 180 MeV/nucleon,  $^{28}\text{Si}$  at 800 MeV/nucleon, and  $^{56}\text{Fe}$  at 500 MeV/nucleon. The CRaTER instrument was mounted on a rotating stage that could be controlled remotely from the counting room. Most of the beam time was spent acquiring data with CRaTER at a variety of angles with respect to the beam axis. The data verified that the features

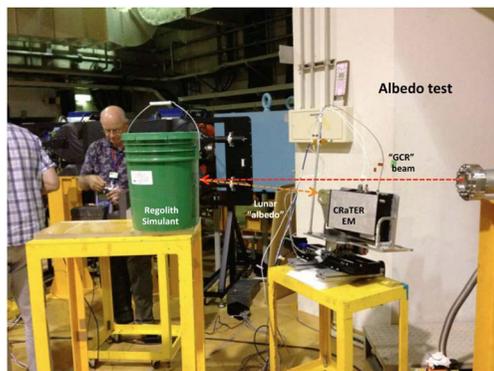


Fig. 4 CRaTER in the HIMAC PH2 beamline (Color online).

seen in the data are caused by out-of-cone particles, and that, as expected, the effect is largest when the incident angle of the particles is close to but just outside the nominal field of view, as reported by.<sup>17)</sup>

In 2013, a different experiment was performed with CRaTER on PH2. A high-intensity proton beam was fired into targets of lunar regolith simulant and polyethylene that were placed at  $0^\circ$  with respect to the beam, with the CRaTER flight spare placed at small angles with respect to the beam. Fig. 4 shows a side view of the beamline configuration, which allowed for the study of backscattered protons produced in the target, similar to the “lunar protons” (also known as albedo protons) that are clearly seen in Crater flight data.

### 2·3 Timepix pixel imaging detectors

Radiation imaging detector technology being developed at the European Organization for Nuclear Research (CERN) has shown great potential for use in radiation dosimetry applications on the International Space Station (ISS), the Orion Multi-Person Crew Vehicle (MPCV) under development for human missions beyond low Earth orbit and future long-term space habitats.

HIMAC has been a vital resource from the earliest phases of the program, by allowing access to heavy

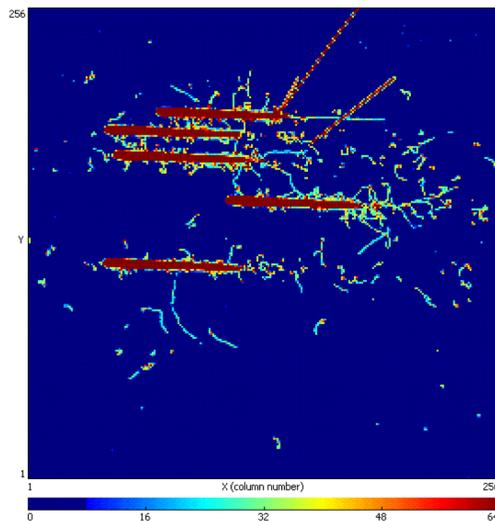


Fig. 5 A single frame from a Timepix detector in the HIMAC Si beam at 800 MeV/nucleon and incident at  $85^\circ$ . Recent HIMAC measurements have been able to use very low intensity beams to isolate single heavy ion tracks (which are more typical of the data seen in space), enabling the measurement over a full range of beam rates (Color online).

ion beams to simulate the potential performance of the much-anticipated Timepix detector chip even before it became available. The Timepix detector chip was designed in 2006 and became available for testing at accelerator beams in 2007.<sup>18)</sup> HIMAC was used initially to do the exploratory characterization of the device’s basic capabilities and to provide precise feedback for the calibration process. Key lessons learned from those earlier HIMAC runs were fed back to the designers of the readout and control interfaces to be ultimately used in space on the ISS and Orion spacecraft.

The Timepix chip has an array of  $256 \times 256$  square pixels, each  $55 \mu\text{m}$  on a side. Charged particles penetrating the sensor layer leave clusters of activated pixels that are reminiscent of tracks in nuclear emulsions as shown in Fig. 5.

Besides being able to sum the net total energy deposited by a particle passing into the sensor, one can make use of the track structure to aid in iden-

tifying both the charge of the particle as well as an estimate of the particle's kinetic energy. One of the key parameters is the amount of energy deposited per unit track-length along its trajectory. Since the energy deposited is measured directly, in order to obtain this value, one needs to know the track-length as precisely as possible. One of the most important contributions obtained from our HIMAC runs is the creation of a database of tracks at precise orientations for a wide range of beam species and energies.

One especially useful aspect of the HIMAC facility is the capability to provide very low intensity beams. In space, the flux of such heavily ionizing particles is very low, so taking data in a very low intensity beam gives us a better simulation of the performance of the detectors in space.

In low Earth orbit (LEO) there is a region of high proton flux known as the South Atlantic Anomaly (SAA). Using a proton beam at HIMAC we were able to simulate an SAA pass by employing the translating stage and slowly moving the detector through the beam. This has continued through the most recent HIMAC runs including exposure of the latest flight hardware called HERA (Hybrid Electronic Radiation Assessor) that is currently planned

for use in the Orion vehicle. In Fig. 6, HERA is shown being calibrated in the HIMAC beam.

The continuing access to HIMAC will be especially valuable to NASA as future generations of this very versatile and successful technology are developed.

#### 2.4 Active Tissue Equivalent Dosimeter for Space Crew Dosimetry and Characterization of the Space Radiation Environment (ATED)

The Radiation Physics Laboratory at Oklahoma State University is developing a low-cost, portable tissue equivalent proportional counter (TEPC) for use in monitoring radiation exposure aboard spacecraft and satellites, as well as on aircraft including commercial jetliners, drones and high altitude balloons. Our TEPC may also be useful in neutron dosimetry applications, e.g. in and around high energy particle accelerator facilities or near nuclear reactors. The first version, referred to as the Active Tissue Equivalent Dosimeter (ATED) was calibrated at HIMAC as part of project H373 and was flown aboard the International Space Station (ISS) in summer 2018. This space experiment was largely successful, in no small part thanks to the characterization of the ATED instrument at HIMAC as shown in Fig. 7.

### 3. Passive Space Radiation Dosimeters

HIMAC has the distinction of being the No. 1 facility in the world for the calibration of passive dosimeter used for area and personal radiation dosimetry in space. Passive detectors used in space dosimetry consist mainly of thermoluminescence and optically stimulated luminescence detectors (TLD and OSLD), and CR-39 plastic nuclear track detector (PNTD), but also include MOSFET dosimeters and photographic nuclear emulsion. Passive space radiation dosimeter from over one dozen laboratories have been calibrated and continue to be calibrated using HIMAC, including the detectors used by

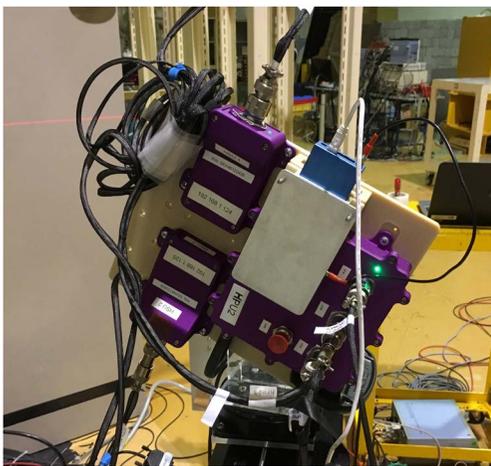


Fig. 6 HERA in position for calibration in the HIMAC PH2 beamline (Color online).

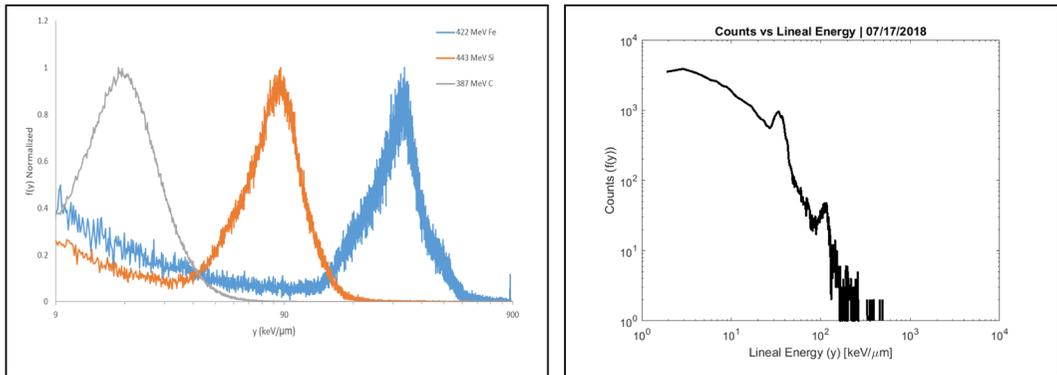


Fig. 7 (left) Lineal energy spectrum for three heavy ion beams measured with the ATED flight unit at HIMAC. (right) Lineal energy spectrum measured by ATED aboard the ISS on 17 July 2018 (Color online).

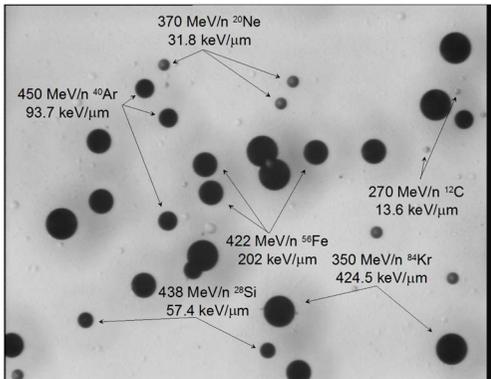


Fig. 8 Photomicrograph of layer of CR-39 PNTD exposed to several different heavy ion beams at HIMAC, following chemical processing. The width of the image is  $\sim 300 \mu\text{m}$ .

JAXA, ESA, RSA and NASA, as well as from other research groups from around the world. As discussed in Section 5.2.2, several research groups calibrated their passive dosimeters at HIMAC prior to the start of the ICCHIBAN program in 2002, it was the ICCHIBAN program that is largely responsible for establishing HIMAC as the go-to ground-based accelerator facility for passive space radiation dosimeter calibration and characterization.

A CR-39 plastic nuclear track detector (PNTD) is a transparent thermoset polymer sensitive to particles of  $\text{LET}_{\infty\text{H}_2\text{O}} \geq 5 \text{ keV}/\mu\text{m}$  and is used in measuring the LET spectrum from heavy charged

particles in space. When a heavy charged particle passes through a layer of CR-39 PNTD, it breaks the molecular bonds of the polymer, leave a trail of latent damage along the particle's trajectory. Post-irradiation chemical processing of the detector dissolves the polymer leaving a conical etch pit, the nuclear track, along the latent damage trail. The size of the elliptical opening of the conical track, normalized to the amount of bulk polymer removed by chemical processing, is proportional to the LET of the heavy charged particle that produced the track. Fig. 8 shows a photomicrograph of a layer of CR-39 PNTD exposed to multiple heavy ion beams at HIMAC, illustrating the relationship of track size to LET.

By exposing layers of PNTD to heavy ion beams of known LET at HIMAC, then chemically processing and analyzing the tracks in the same was as PNTD layers exposed in space, a detector response function can be generated relating normalized track size to LET. Fig. 9 shows response functions for two different chemical processing regimes for type USF-4 CR-39 PNTD calibrated with heavy ion beams at HIMAC.

TLD and OSLD are routinely used to measure the total absorbed dose received by astronauts and cosmonauts during spaceflight. However, TLD and OSLD under-respond to  $\text{LET} < \sim 10 \text{ keV}/\mu\text{m}$ , mean-

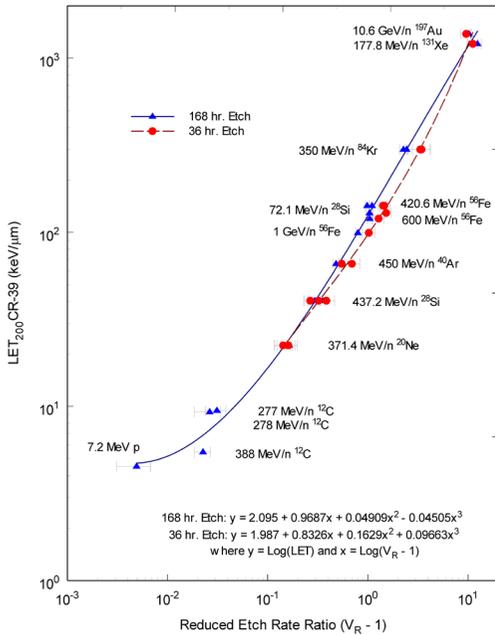


Fig. 9 Detector Response Function for Type USF-4 CR-39 PNTD (Color online).

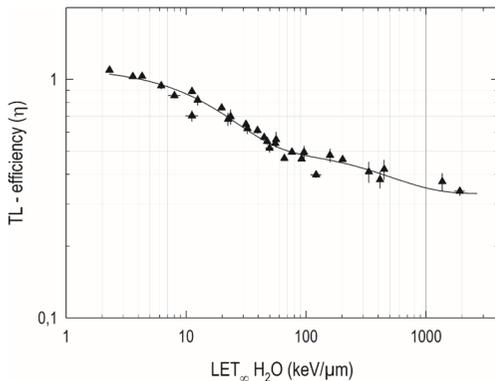


Fig. 10 The thermo-luminescence (TL) detector efficiency detecting heavy ions as encountered in space radiation fields (DLR).<sup>8)</sup>

ing that for a particular dose of high LET radiation, e.g. 200 keV/μm from a 500 MeV/nucleon <sup>56</sup>Fe beam, produces less signal in the detector than an identical dose of low LET radiation, e.g. 0.1 keV/μm from a 150 MeV proton beam. In using TLDs and OSLD for space dosimetry, it is necessary to find the dose registration efficiency as a function of LET and the use of the wide selection of heavy ion beams of

different energy at HIMAC is ideal for this purpose. Fig. 10 shows an efficiency curve for one type of TLD (TLD-100) as a function of LET, measured using beams at HIMAC by DLR.<sup>8)</sup> Dose registration efficiency decreases with decreasing LET. A correction can be made based on the LET spectrum measured in another instrument, e.g. CR-39 PNTD or a TEPC.<sup>19)</sup>

#### 4. Conclusion

The above examples illustrate the remarkable versatility of HIMAC in delivering particle beams across a wide range in atomic number, energy and intensity. HIMAC remains one of the preeminent ground-based facilities for calibration and testing of space radiation detectors. Over the years, NIRS has hosted numerous international symposia and meetings including the 10th Workshop on Radiation Monitoring for the International Space Station (2005) and the Heavy Ion Therapy and Space Radiation Symposium 2013 (HITSRS2013). In addition several national space agencies have established official international collaboration agreements with QST or QST-NIRS. Largely thanks to HIMAC research, NIRS has become an internationally recognized center for space radiation research.

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