Nuclear Instruments and Methods in Physics Research B 365 (2015) 414–418

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

A simple ion implanter for material modifications in agriculture and gemmology

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ARTICLE INFO

Article history:
Received 1 October 2014
Received in revised form 6 April 2015
Accepted 15 July 2015
Available online 28 July 2015

Keywords:
Ion implanter
Ion beam modification
Rice
Gemstone

ABSTRACT

In our efforts in developing ion beam technology for novel applications in biology and gemmology, an economic simple compact ion implanter especially for the purpose was constructed. The designing of the machine was aimed at providing our users with a simple, economic, user friendly, convenient and easily operateable ion implanter for ion implantation of biological living materials and gemstones for biotechnological applications and modification of gemstones, which would eventually contribute to the national agriculture, biomedicine and gem-industry developments. The machine was in a vertical setup so that the samples could be placed horizontally and even without fixing; in a non-mass-analyzing ion implanter style using mixed molecular and atomic nitrogen (N) ions so that material modifications could be more effective; equipped with a focusing/defocusing lens and an *X–Y* beam scanner so that a broad beam could be possible; and also equipped with a relatively small target chamber so that living biological samples could survive from the vacuum period during ion implantation. To save equipment materials and costs, most of the components of the machine were taken from decommissioned ion beam facilities. The maximum accelerating voltage of the accelerator was 100 kV, ideally necessary for crop mutation induction and gem modification by ion beams from our experience. N-ion implantation of local rice seeds and cut gemstones was carried out. Various phenotype changes of grown rice from the ion-implanted seeds and improvements in gemmological quality of the ion-bombarded gemstones were observed. The success in development of such a low-cost and simple-structured ion implanter provides developing countries with a model of utilizing our limited resources to develop novel accelerator-based technologies and applications.

1. Introduction

In developing countries such as Thailand, developing advanced technologies such as accelerator technology is possible but usually constrained by limited budgets and also usually targeting at those fields the nation urgently requires for economic growth and local people's needs such as agriculture and some national special industries. In Thailand rice is the most important food crop for feeding people as well as exporting. Constantly improving local rice quality is a continuous task for meeting international competition and raising local people's health and income. Developing genetic mutation of rice is one of the effective choices. Among a number of mutational techniques, the recently developed low-energy ion beam biotechnology [1] in the country has been becoming a powerful tool for the purpose [2–4]. In ion beam biotechnology, ion implanters conventionally applied to ion implantation of solid materials have been used for ion beam bombardment of biological living samples. But, the operation is not convenient and beam line conditions are sometimes not satisfied for maintaining the living biological materials. Therefore a specialized ion implanter has been needed. In Thailand gemstone industry has been an important local industry for national revenue. Recently ion beams have been found to act as a unique treatment measure to improve gemstone quality and thus increase the commercial

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http://dx.doi.org/10.1016/j.nimb.2015.07.066

values [5]. In the same situation as that for ion beam biotechnology, previously conventional ion implanters were used for ion implantation of gemstones but operation was inconvenient. Both biological samples such as rice seeds and plant tissues and gemstone samples such as cut jewelleries have irregular sizes and shapes which make the sample fixing in vertical very difficult if the ion beam line is horizontal. Both types of samples should not be exposed to ion beam for too long time otherwise the biological samples would die and gemstones would receive additional heat treatment from the beam irradiation. Moreover, in service to our customers of agriculture and gem industry, if the users can join in the operation, the ion beam treatment may increase its efficiency and effectiveness. Therefore, a biotechnology- and gemmology-specialized, simply structured and user-friendly vertical compact ion implanter became necessary. The designing of the machine was aimed at providing our users with user friendly, convenient and easy operation of a simple and economic ion implanter for ion implantation of biological living materials and gemstones for crop mutation induction as well as for modification of gemstones, which would eventually contribute to the national agriculture, biomedicine and gem-industry developments.

2. The ion implanter

The completed ion implanter system is shown in Fig. 1. The implanter itself consists of a duoplasmatron ion source, a 100-kV accelerating tube, a small beam diagnosis chamber, an electrical x–y scanner and a target chamber. The beam line is evacuated by a powerful diffusion pump system and supplied by various power supplies. It should be particularly mentioned that all components of the machine came from our decommissioned accelerator machines and hence they were reused for greatly saving budget.

The ion source was of a duoplasmatron type with certain modifications (Fig. 2), originally used at our dismantled high-current non-mass-analyzing ion implanter for industrial applications. The ion source could be separated into two parts, a plasma generator and an extraction system. The first part included a filament cathode, an intermediate electrode and an anode. The second part consisted of two or three electrodes which were anode, extractor and ground. In order to find optimized operation conditions, both parts were intensively investigated. After testing the ionization process, the nitrogen plasma was stable about 60 min with an arc current of 2.0 A and an arc voltage about 80–85 V, which was in agreement with the theory on the general property of the arc discharge [6], and the arc pressure was 6×10^{-1} Torr which was related to the sufficiency of the gas supply rate. The extraction voltage was normally fixed at 6 kV after optimization though its capacity was 15 kV. The accelerating tube was from a decommissioned 400-kV medium-energy ion beam analysis accelerator and modified with shortening. The beam emittance was measured based on the transformation matrix theory using a pepper pot plate at the beam diagnosis chamber (Fig. 3) to be $\varepsilon_x = 1.62$ mm mrad. The electric x–y scanner (Fig. 4) was obtained from an uncompleted home-made secondary ion mass spectrometer. The 2-m-high ion implanter, without mass analysis, was able to accelerate ion beam of such as nitrogen and argon with the maximum voltage of 100 kV with a maximum current of about 1 mA, which was enough for ion beam modification of biological living materials and gemstones. The target chamber was deliberately made relatively small so that the pumping time could be short for maintaining biological samples alive. Inside the target chamber there were a sample holder stage and a beam current measurement plate which coordinated a Faraday cup in the beam diagnosis chamber to check the beam current. At the target the ion beam bombarding area could be as large as 100 cm^2 which made simultaneous ion implantation of a thousand rice seeds or tens of gemstone samples possible. A stack of power supplies and controllers managed the operation of the facility. To make the ion implanter user-friendly, the operation was computer-controlled. The whole system was housed in an appropriately-sized air-conditioned room to reduce the humidity from the tropical environment.

In most cases of ion implantation, nitrogen ion beam was applied. Since the system was a non-mass-analyzing ion implanter, it could offer a higher beam current of mixed atomic and molecular nitrogen ions in a normal ratio of 1:4. As a N_2^+ ion would be broken into two atomic nitrogen ion/atoms as soon as it hit the target surface and then each atomic particle had energy half that the original ion had, the N-ion implantation could bring a broader ion depth profile in the target material due to two energies of ions. Both higher beam current and broad ion distribution were just needed by applications of ion beam biotechnology and gemmology as in these cases the factor of ion species was not critical.

3. Application in materials modification

The ion implanter has been put into applications of ion implantation of local rice seeds to induce mutation and local corundum

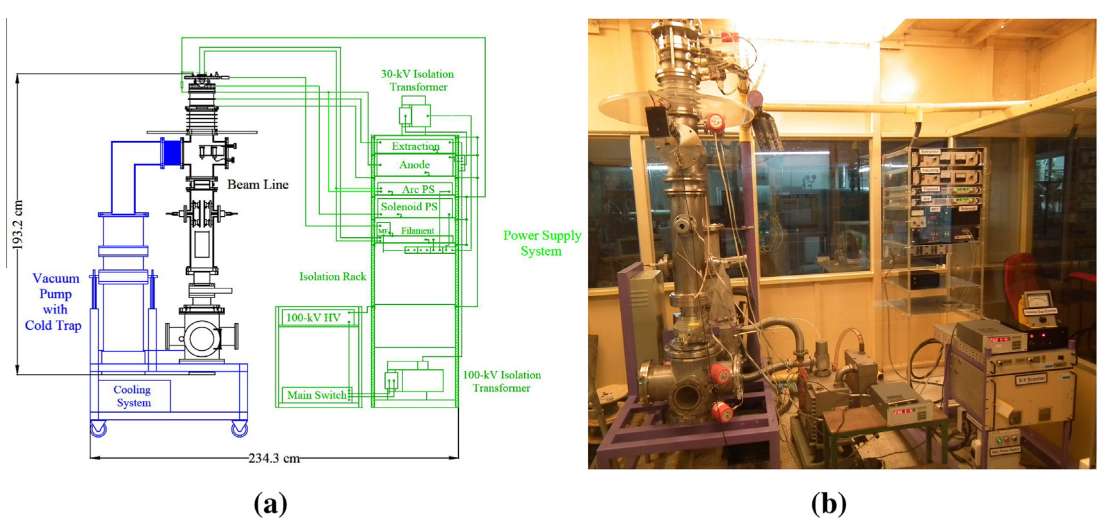

Fig. 1. The completed simple and economic compact ion implanter system at Chiang Mai University. (a) Schematic diagram. (b) Photograph (front view). At the left side is the vertical ion implanter and at the right side is the power supply stack.

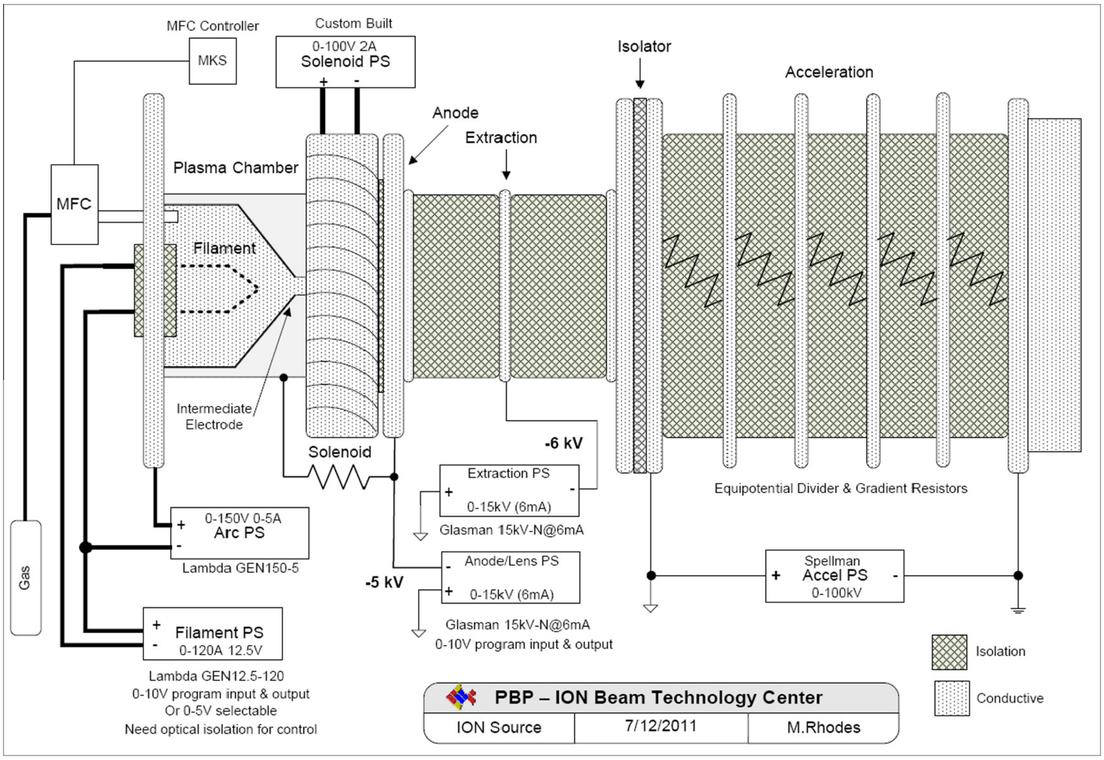

Fig. 2. Schematic diagram of high-voltage terminal system including the duoplasmatron ion source and the home-modified accelerating tube with their power supplies.

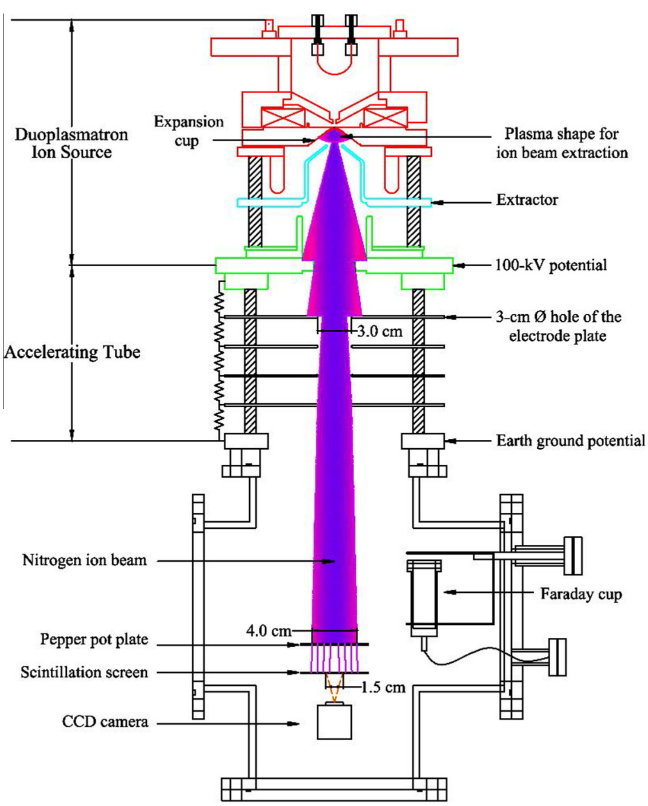

Fig. 3. Schematic of the beam emittance measurement and the beam profile in the ion source and the accelerating tube and afterward.

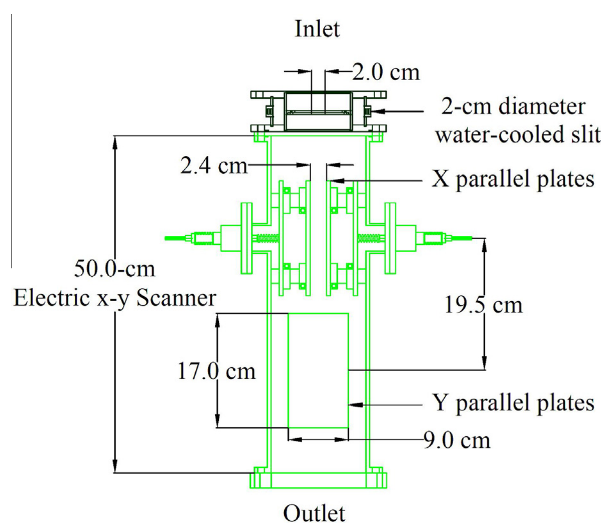

Fig. 4. Schematic diagram of the electrical *x*–*y* scanner.

samples to improve their optical quality. A special rice seed holder which was made from copper for better dissipating ion-beam heating with hundreds of holes, as shown in Fig. 5, was used to hold hundreds of seeds in the holes. The seed embryo tips were first exposed by peeling the coat and erected in the holes to face the ion beam coming direction. For inducing mutation, N-ion beam was normally applied with ion energy around 30–60 keV and fluences in an order of at least 10^{16} ions/cm^2. After ion beam bombardment, the rice seeds were planted, survival rate was measured and mutation was screened during the whole growing period till harvest. The results showed that at a survival rate of normally about 50%, a mutation frequency could be about 1/1000. Several local rice varieties were used in the experiment, including Khaokum Doisaket rice, Sangyod Phatthalung rice and RD 6 rice. As shown in Fig. 6, various phenotypic changes from the wild types were found after ion

Fig. 5. Photograph of the specially designed rice seed sample holder. Rice seeds are being held in the holes of the holder.

implantation of the seeds and confirmed to be mutations. These changes included appearance in such as height, color and number of stems, photoperiod sensitivity, grain size and color, and glutinousness. Beneficial mutations with characters of, for instance, shorter straw, photoperiod insensitivity, larger grain and higher glutinousness were selected for stabilization and preparation for further development and distribution. The short-straw mutant decreased the rice stem by about 30% so that the stem strength could be increased and fertilizer could be consumed less. The photoperiod insensitivity mutant released the rice planting period to more flexible periods in a year. The larger grain mutant certainly increased the rice yield by several to about 10%. The higher glutinousness mutant improved the cooked rice taste. Mechanisms involved in ion-beam-induced mutation have been investigated and introduced in terms of direct and indirect interactions between the ions and DNA in the cell (e.g. [1]). Energetic ions are able to penetrate the biological cell envelope to interact directly with DNA inside the cell nucleus owing to abnormally large projectile ranges in the porous polymeric cell envelope materials to change DNA [7]. On the other hand, ion implantation in the living materials is able to generate reactive free radicals which can indirectly interact with DNA and thus change DNA [8]. Hence mutations are possible when the induced DNA changes are misrepaired.

Local corundum from a variety of customers was ion-beam treated at the ion implanter. Heat treatment has been the traditional method to improve gemstone qualities, but the drawbacks were very high temperature and long time which cause inconvenience and unable to treat locally on the stone defects. But, particle beams can be an alternative to treat gemstones as they can locally deposit high energy to remedy defects and also treat the entire stone surface. However, corundum is hard to be improved by electron beam irradiation as used for treating other gemstones but could be modified by ion beams. In ion implantation, gemstone samples, no matter their size and shapes, were easily and simply placed in a special tray in horizontal as the beam line was vertical without necessary fixing, as shown in Fig. 7. The ion beam was nitrogen, accelerated by 40 kV so that two N-ion energies of 40 keV and 20 keV could be obtained, and beam fluences were in an order of 10^{17} ions/cm^2. In normal treatment two sides of the samples were ion-implanted respectively. After ion beam treatment, the corundum became more transparent, shining and clear, the color was more homogeneous, and originally existing flaws disappeared (Fig. 8). The gemmological professionals judged the gem grade and confirmed the grade increased. For example, ion

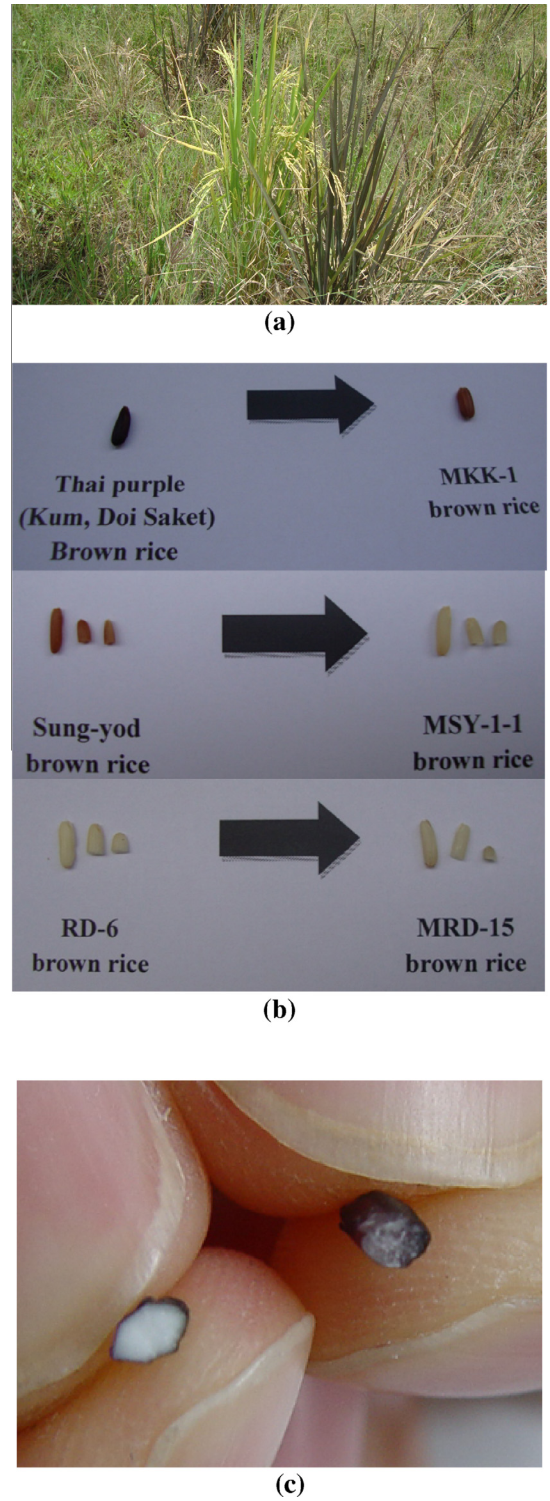

Fig. 6. Phenotypic changes of ion-beam-induced rice mutants. (a) Appearance: right – wild type (KhaoKum, Doisaket rice; Thai Purple rice), and left – its mutant named as MKK-1. (b) Phenotypic variations found in Thai Purple rice mutant (MKK-1) include photoperiod insensitivity, seed size and color of brown rice, in Sangyod Phatthalung rice mutant (MSY-1-1) include photoperiod insensitivity, seed size and color of brown rice, and in RD 6 rice mutant (MRD-15) include photoperiod insensitivity, seed size and glutinous rice to non-glutinous rice. (c) Rice grain inner color change: right – wild type rice, and left – mutant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

implantation changed blue sapphire in the color grade from B (blue) to BV (blue + violet) and the color saturation grade from 7 to 8, change white sapphire in the color grade from colorless to

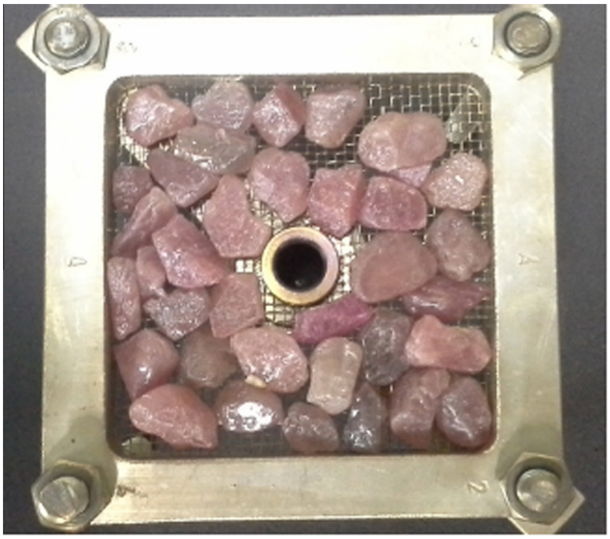

Fig. 7. Natural sapphire stones are held in the sample holder for ion implantation.

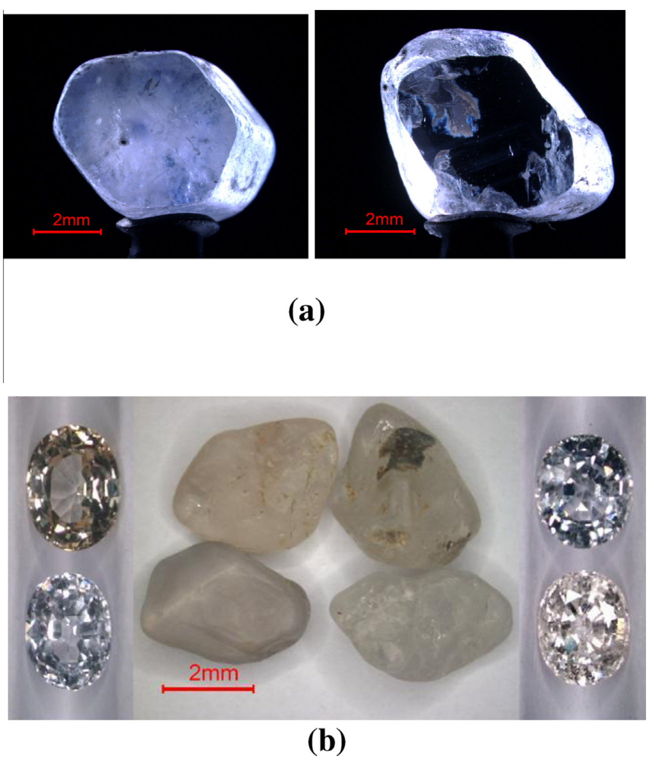

Fig. 8. Photographs of ion-beam modification of gemstones. (a) White sapphire before (left) and after (right) N-ion implantation. The front side of the sapphire is a cut surface which is the ion implanted side. (b) Original low-quality sapphire (at the center) became high-quality jewellery (at two sides) after N-ion implantation and cut.

B, the color tone grade from nothing to 4 and the color saturation from nothing to 4, and changed green sapphire in the color grade from G (green) to BG, the color tone from 1 to 3 and the color saturation from 5 to 7. Mechanisms of ion-beam-induced gemmological modifications have preliminarily been studied and interpreted [5,9]. The main cause could be the changes in oxidation states of impurity metals, induction of charge transfer from one metal cation to other and the production of color centers.

4. Conclusion

The simple vertical ion implanter has been constructed and installed at Chiang Mai University. The machine was featured with simple structure, low cost, and user-friendly operation particularly for applications in biotechnology and gemmology. The ion implanter has been applied to successfully induce local rice mutation and improve local corundum quality. The success in development of such a low-cost and simple-structured ion accelerator/implanter provides developing countries with a model of utilizing our limited resources to develop novel accelerator-based technologies and applications.

Acknowledgements

The work was supported by Chiang Mai University (CMU), the Thailand Center of Excellence in Physics (ThEP), the National Research Council of Thailand (NRCT), and the International Atomic Energy Agency (IAEA).

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