Liquid Ionization Chambers for Radiation Therapy

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Abstract— **Liquid ionization chambers are described to be used as monitors in radiation therapy. The development focuses on two areas of application, an on-line monitor for intensity modulated radiation therapy and the measurement of the energy deposit of heavy ions in tissue. This requires a thin detector with two-dimensional read-out and an absorbing chamber with three-dimensional read-out, respectively. Both detectors are realized using similar techniques. First measurements with prototype chambers are described. The liquids isooctane, isononane (TMP), and tetramethylsilane (TMS) are used in a high purity grade in order to realize high current signals for electronic read-out in parallel at frequencies exceeding 10 Hz. Signals of more than a factor 4 with respect to isooctane, analysis grade, are obtained. With an electrode structure of 400 pads in a two-dimensional geometry an uniformity in efficiency within 1.2 % has been measured.**

Index Terms— **on-line monitor, liquid ionization chamber, IMRT, ion therapy**

I. Introduction

MODERN radiotherapy aims to improve cancer treatment by forming x-ray or ion beams specific to the individual tumor shape. Aim is to deposit energy at the tumor site without damaging the surrounding healthy tissue. In particular, organs-at-risk have to be avoided when applying the necessary dose to the (planning) target volume. For example, for prostate therapy suitable blocking leads to less radiation induced proctitis and bleeding.

Clinical approved techniques consist of shaping the radiation beams by collimators and applying them from different directions to the patient. Important new tools for 3D radiation therapy are intensity modulated beams shaped with dynamic collimators, mostly multileaf collimators. They provide an additional degree of freedom to tune the delivered dose with flexibility at each point of the treatment volume. Intensity modulation, however, requires an increased effort in on-line monitoring to guarantee safety and reproducibility. As Webb [1] has pointed out, for dynamic multileaf collimators verification is an important issue. Moving components greatly jeopardize the safety of radiation therapy. Hence, the quality of dynamic radiation application has to be assured conscientiously.

Research in this direction is the objective of developing a liquid ionization chamber to monitor the radiation directly and instantaneously at the collimator exit before being applied to the patient. The chamber has to verify the individual settings of the leaf positions and the corresponding shape of the beam. For this purpose it should be thin in order to absorb and disperse the radiation at minimum. Pixel sizes should have similar dimensions as the collimator leafs, viz. in the few square millimeter range. The read-out should be two-dimensional and directly with a repetition rate of several 10 Hz to cope with the leaf speed which usually is in the order of cm/s. To deliver a reasonable noise-free picture, the chamber has to generate a relatively high current signal for typical dose rates of 3 Gy/min. This requires a dense medium, e.g. a liquid. Currents typically obtained in gas-filled chambers are much smaller.

The liquid commonly used in ionization chambers for medical application is isooctane, examples are electronic portal imaging devices. They are used in a voltage switched operation and require a different theoretical treatment. For a review see [2] and on the physical aspects of liquid-filled matrix ionization chambers [3]. Application of isooctane ionization chambers for precision dosimetry has been discussed in [4]. The liquids have been used in an analysis grade purity, since the currents of positive and negative ions are of relevance in the read-out mode used in portal imaging devices and for long-term usage.

In the following we report on measurements with purified isooctane and additionally using the liquids isononane (tetramethylpentane, TMP) and tetramethylsilane (TMS). The latter two liquids are known to have large yields of excess electrons when irradiated with ionizing radiation. All liquids are used in a high purity grade, viz. purities in the range of a few ppb oxygen equivalent, in order to investigate the contribution of free electrons to the current signal. The high mobility of electrons is anticipated to reduce the space charge effects of slow moving ions when relative thick layers of liquids have to be applied. At least the hampering influence of negative space charge should be reduced. Also, the ion mobilities are slightly higher in purified liquids as has been pointed out in [5]. The set-up of a two-dimensional chamber is described in section II, followed by results from first tests as presented in section III.

A second possible application of liquid ionization chambers is an energy monitor in heavy ion therapy. Beams of fast ions like carbon represent an advanced tool for radiotherapy of deep seated tumors. They combine an excellent physical depth-dose profile (Bragg curve) with an increased relative biological efficiency in the target volume. In order to measure the energy deposit as function of depth realisticaly, a three-dimensional read-out is required and the physical properties of the absorber medium have to be similar to human tissue. Gaseous detectors

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would require layers of thick absorber material in between the individual detector layers to obtain the required total absorption. The ionization liquids used have physical properties, which are almost equivalent to human tissue. Thus, the liquids can be used to build a homogeneous detector (or calorimeter), in which the active detection medium serves also as absorber material. To test this method, a three-dimensional chamber has been developed as described in section IV.

II. A CHAMBER WITH TWO-DIMENSIONAL READ-OUT

A. Set-up of the chamber

The chamber has been designed to test the liquids and to gain experience with the principal components of an envisaged monitor chamber [6]. The dimensions and the frame have been chosen to be used gantry mounted with a miniature multileaf collimator[1] and a x-ray beam of a linear accelerator[2] at the German Cancer Research Center (DKFZ). A schematic view of the chamber is shown in Figure 1. The aperture of the collimator is 70×84 mm^2. The entrance and exit windows are of special inert plastic material[3], which with its low mean atomic number is sufficiently transparent for x-rays and is flexible enough to allow for temperature and pressure variations.

The distance between the electrodes has been chosen to 5 mm in order to maximize the signal and to minimize the electronic noise. The voltage (up to 5 kV) is applied to the cathode which consists of a thin nickel mesh fixed to a ceramic frame with indium solder. The pad structure of the anode is realized as a silver palladium conductor on a 0.63 mm thick ceramic substrate. Its structure is shown in Figure 2. No special processing like electric polishing or other methods had been applied to smooth the pad structure. The pad rows are aligned with the collimator leafs and the pad size of 3.3×4.0 mm^2 and the spacing of 0.2 mm is adapted to the leaf width of 1.75 mm. The positions of two adjacent leafs are controlled by one row of pads[4]. The 400 pads are surrounded by a guard electrode (3.5 mm wide rectangular frame) in order to form an adequate homogeneous electric field at the edges.

[1] ModuLeaf, MRC Systems GmbH, Heidelberg, Germany
[2] PRIMUS, 6/15 MV, Siemens OCS, Concord, California, USA
[3] VECTRA
[4] viz. 3.3 mm + 0.2 mm= 2×1.75 mm

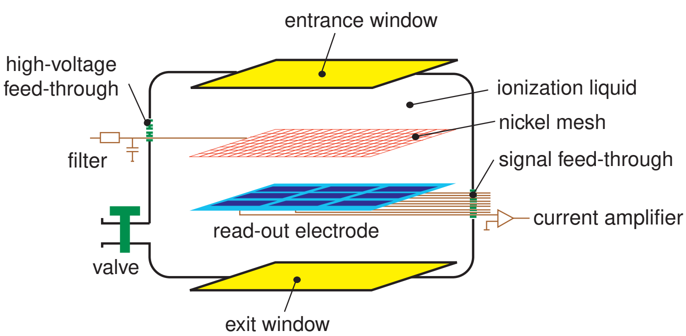

Fig. 1. Schematic view of a test chamber with two-dimensional read-out.

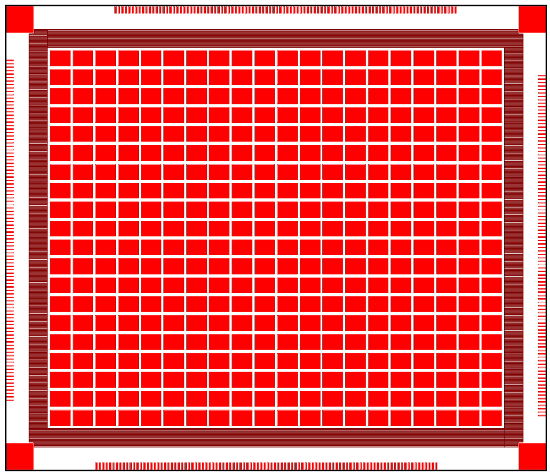

Fig. 2. The anode is segmented in 20×20 pads surrounded by a field electrode of 3.5 mm width.

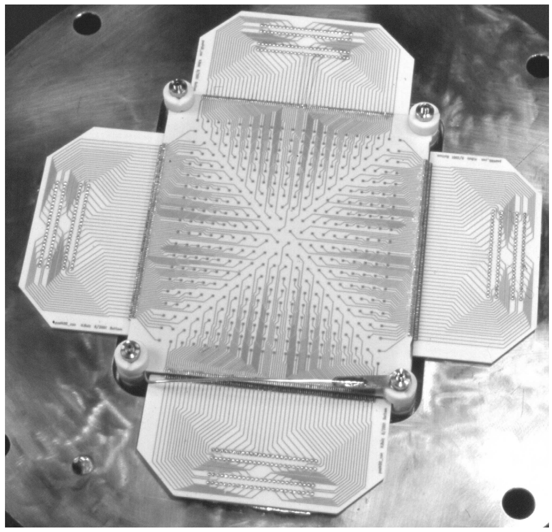

Fig. 3. Photograph of the rear side of the anode attached to the exit flange. Noticeable are also the four boards leading the read-out tracks to four feed-through plugs.

Electronically the anodes are on virtual ground and the field shaping electrode is on ground potential. Each pad is connected to a circuit track on the rear side of the ceramic substrate. Figure 3 shows a photo of the circuit track system which traces the signals to four feed-through plugs. The tracks have a width of 125 μm and approach each other 250 μm at most.

B. Chamber and Liquid Purification

After assembling and wire soldering the residues are removed with a defluxer liquid[5]. Afterwards, the chamber is purified in an alkaline ultrasonic bath and rinsed several times with de-salinated water. Following this chemical cleaning the chamber is further purified by rinsing with clean TMS until the liquid stays in its purity in the chamber for several days. Normally, this means filling and emptying the chamber half a dozen times.

[5] Axarel 130 G, Alpha-Fry Technologies

The liquids are used either in an analysis grade purity, typically 99.5 % or purified to a few ppb of oxygen equivalent. Purification is performed in a distillation facility on site [7]. The liquids are distilled in vacuo and passed over molecular sieves several times until single pulses of electrons (from a ^{210}Bi source) can be observed in an ionization chamber filled with the liquid. For TMS and TMP this happens at a purity of 10-50 ppb.

C. Electronic Read-out

Typical currents to be measured are around 1 nA per pad at a voltage of 1 kV. These currents are read out and digitized using two commercial front-end boards[6], with 256 individual ADC channels each. The boards are based on the TERA03 VLSI recycling capacitor chip [8]. The ADC is capable to measure currents of 0.1 to 1000 nA in each channel with an accuracy of 1 %. The currents are integrated on input capacitances and the charges converted to 16-bit digital signals. For the present investigations an integration time of 100 ms has been chosen. Control measurements at typical currents of 1 nA have shown that indeed the current is determined in 100 ms with an relative rms of 0.8 %. The scale is calibrated by feeding a constant current from a pico ampere source to one channel of a board. A good linearity between 0.1 and 100 nA has been found which is well reproducible. The ADC is controlled via a digital I/O card[7] hosted in a PC.

D. Monitor concept

As described in the introduction, the liquid ionization chamber is to be used to monitor the individual settings of the leaf positions of a MLC. However, the actual number of 400 pads does not provide a sufficiently accurate resolution, i.e. less than 1 mm in the direction of the leaf movement. Therefore, the monitor function must be based on a concept different from simply creating an image of leaf positions.

The idea of using the liquid ionization chamber as a dose monitor that is sensitive to leaf position is based on the three following items:

a) Each pad must have a dimension in the direction perpendicular to the leaf movement which exactly matches the leaf thickness projected to the distance of the monitor's entrance foil from the focus. Consequently, the signal of each pad is unambiguously related to a certain leaf. For the prototype described in this paper, two leaves are considered to represent a single leaf.

b) Due to the technical constraints in the pad structure and also in the electronic read-out system, the number of pads (and hence the geometrical resolution) cannot be increased arbitrarily. Therefore, the size of a pad in the direction leaf movement will usually exceed several millimeters. However, a pad which is only partly irradiated (i.e. the leaf edge position is projected somewhere within the pad area) will produce a signal between a minimum (the pad is under the leaf) and a maximum (fully irradiated). Since such a signal can be pre-calculated, the comparison and agreement between a pre-calculated value and the actually measured value can then be used to monitor any leaf edge position also at partial pad irradiation.

c) The electronic read-out system offers the information of all pad signals in a parallel mode at a time resolution of about 10-50 Hz. At present, the integration time for the read-out is 100 ms. The pulse repetition frequency of the accelerator is 200 Hz. Hence, the comparison and the position monitoring can be performed in a cycling mode close to the pulse repetition frequency of the accelerator. Thus dose monitoring appears well feasible also for dynamic IMRT.

[6]FE4C, PHYSALUS, Novara, Italy

[7]PCI-DIO-32HS, National Instruments

III. Results

A. Imaging properties

The homogeneity of response for uniform irradiation is presented in Figure 4 (left). The measurements were performed at a ^{60}Co source[8] at the DKFZ, applying a dose rate of 0.24 Gy/min at a distance from the focus to the phantom of 80 cm in a depth corresponding to 5 cm water equivalent at a field size of 10×10 cm^2. In the central region a good homogeneity can be stated. At the four corners, however, inhomogeneities of the voltage field attract more current from outside and as a result more charge is registered. Obviously, the guard electrode around the pad structure was not wide enough to ensure parallel field lines all over the anode surface. Excluding 24 channels from the four corners one obtains the signal distribution as shown in Figure 4 (right). A Gaussian fit yields a σ-value of 1.5 %. When subtracting the electronic noise fluctuations of 0.8 % mentioned in section II-C, one can conclude that the spatial homogeneity varies within 1.2 % only. A similar homogeneous response has been observed for pulsed radiation from a linear accelerator.

The chamber has been operated in the horizontal position. Turning it by 180°, viz. using the rear side as entrance, did not change the results noticeably within a two-sigma value. This signifies that the cathode mesh was well tightened and that the electrodes distance stayed constant, independently of the chamber inclination. Further tests will examine the effects of different chamber inclinations in more detail. Due to the

[8]Gammatron S80, Siemens AG, Germany

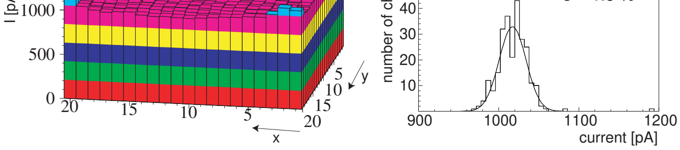

Fig. 4. Response for a uniform irradiation from a ^{60}Co source. Operated with TMS at 2 kV/cm. Left: Spatial distribution of the read-out current. Right: Frequency distribution of read-out current.

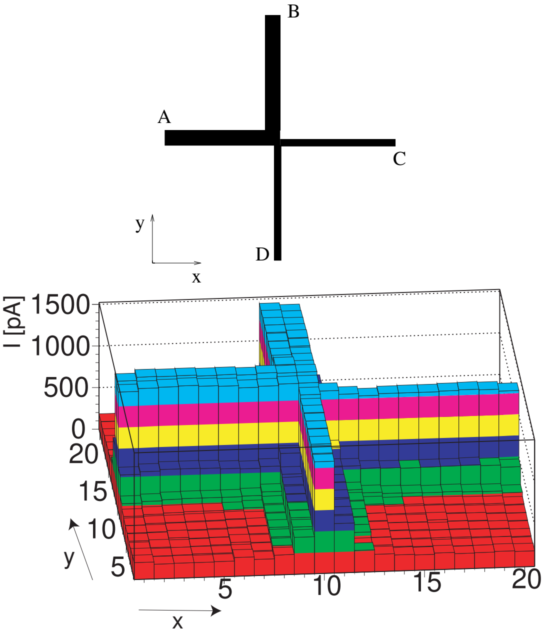

Fig. 5. Top: Aperture of collimator, arms A and B are two pads wide, arms C and D have a width of one pad. Bottom: Signal response for a cross formed with a MLC at the electron linac. Operated with isooctane at 2 kV/cm.

small aperture dimensions of the collimator and, therefore, the relative rigid construction of the chamber no significant changes are expected.

The uniform distribution also remained stable when increasing the cathode voltage up to 2 kV (4 kV/cm). At higher voltages for several channels the current increased and started to fluctuate stochastically, probably due to local micro spikes on the anode track structure. To be on the safe side, most measurements were performed at 1 kV (2 kV/cm).

Different collimator apertures have been tested with x-rays generated with a linear accelerator. The measurements have been performed at a dose rate of 2 Gy/min. The ModuLeaf collimator has been used to test how well the leaf positions of the collimator can be checked on-line.

In Figure 5 the current image of an asymmetrical cross formed with the collimator is shown. The upper graph represents the collimator aperture: the broad arms are 7 mm wide (corresponding to 4 leafs) and the thin arms have a width of 3.5 mm. The cross has been chosen to test the consistency of detection and read-out in x as well as in y-direction. The lower graph shows the measured currents. The results confirm an uniform sensitivity, the two arms A and B deviate in their signal sum by less than 1.5 %. The difference in the thin arms is (slightly) higher, viz. 3 %, probably caused by the slight misalignment between the chamber rows and the collimator leafs. The signals in the adjacent regions of the cross are well explainable with a penumbra width of 2 mm. The background currents of about 200 pA were caused by an accidental pick-up of high frequency in the transmission lines. The fault has been removed and does no longer exist in the actual measurements.

In conclusion, it can be stated that the chamber exhibits stability of performance and shows uniformity in sensitivity and read-out.

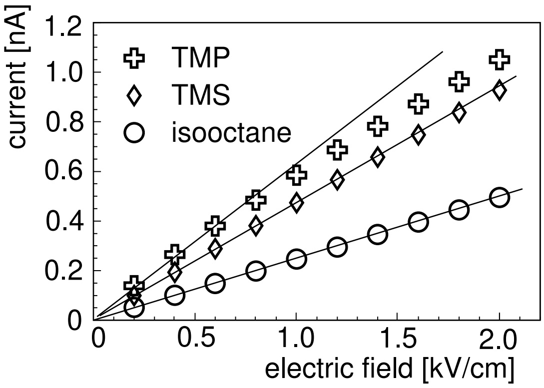

Fig. 6. Ionization current for the indicated liquids at a dose rate of 0.44 Gy/min versus electric field, measured at a ^{60}Co source. The straight lines represent fits to the current values below 1 kV/cm.

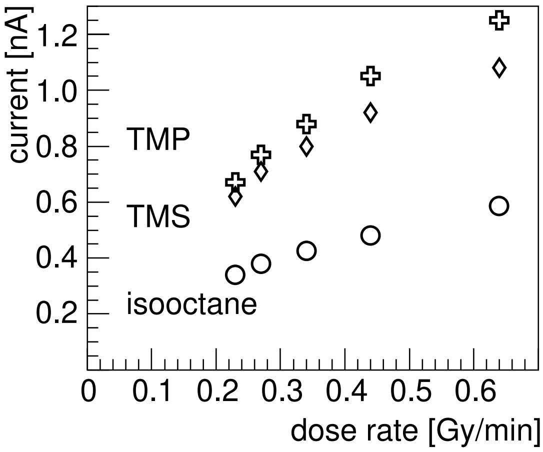

Fig. 7. Measured current versus dose rate at an electric field of 2 kV/cm for the indicated liquids at a ^{60}Co source.

B. Signal Response

Ionization currents for different dose rates have been measured at the Gammatron by varying the chamber position for rates between 0.23 and 0.64 Gy/min with respect to the applied voltage. As an example Figure 6 shows the current for 0.44 Gy/min with respect to the applied electric field. One observes that the two liquids with a high value of $G(0)$ yield higher currents when compared with isooctane, roughly by a factor of two. At a voltage field of 2 kV/cm the mean values of all central channels amount to 1.05 nA for TMP and 0.92 nA for TMS as compared to 0.48 nA for isooctane. These values account for purified liquids. Isooctane was also measured unpurified, i.e. as delivered from the factory, and yielded half the current. At 2 kV/cm, 0.23 nA were obtained. As a result it can be quoted that for purified TMP the current signal is increased by a factor 4.4 with respect to isooctane, analysis grade.

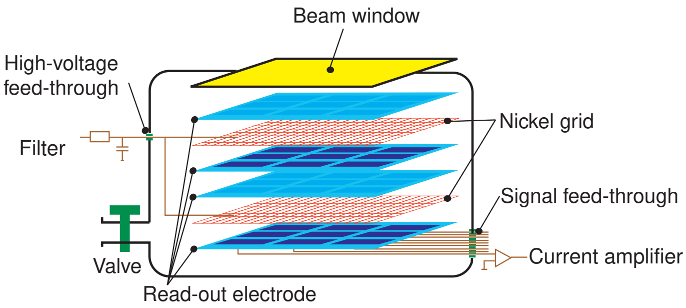

Fig. 8. Schematic view of a test chamber with three-dimensional read-out. The chamber contains four layers of read-out electrodes, interspaced with two nickel grids to apply high voltage.

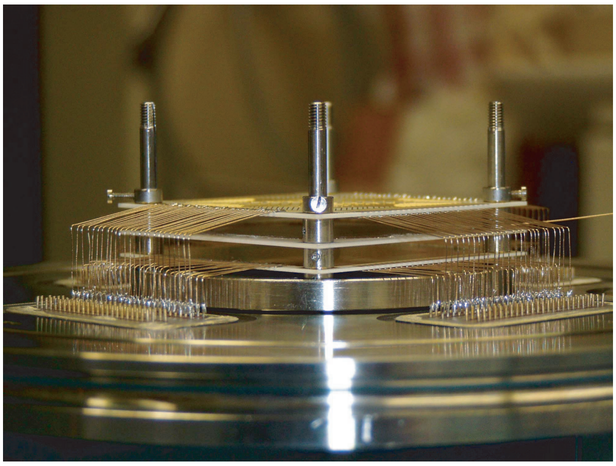

Fig. 9. Photograph of the read-out electrodes of a chamber with three-dimensional resolution. The individual pads on the anodes (top and bottom layer) are connected with wires to the ceramic feed-through in the chamber lid. Also visible is the frame for the kathode mesh, centered between the two anode layers.

For TMP the transition from the domain of initial recombination to general or volume recombination can be seen. Figure 6 shows the current as function of the electric field. For TMP the strong rise at low fields flattens above field strengths around 1 kV/cm. In this liquid, and indicatively in TMS, the ejected electrons are easier prevented to recombine with their mother ions due to their high mobilities. Thus, at low voltages the current increases fast with respect to the electric field. This flattening in the current rise has been observed at similar field strengths also by Johansson et al. [9].

In Figure 7 the currents at a polarizing voltage of 2 kV/cm are shown as a function of the dose rate. For all liquids the current exhibits a slightly non-linear correlation with the dose rate.

IV. A CHAMBER WITH THREE-DIMENSIONAL READ-OUT

The measurement of the energy deposit as function of the depth in a medium requires a monitor with three-dimensional read-out. To test this approach a chamber with four planes of read-out electrodes has been built. Each layer contains 10×10 pads with the dimensions 2.5×2.5 mm. Two pairs of anode layers are arranged as scetched in Figure 8. In each layer pair the anode pads are facing each other. The high voltage is applied to two nickel grids, arranged in the center plane of each pair of anode layers. The distance between the nickel grid and the read-out layers has been choosen to be 4 mm. The materials used and the read-out electronics are identical to the set-up of the chamber with two-dimensional read-out as described in section II. A photograph of the set-up for the first two layers is shown in Figure 9.

First tests of this chamber have been conducted at a ^{60}Co-source at the DKFZ in Heidelberg. It could be demonstrated that a homogeneous read out can be achived with this device. To verify the capability to measure the Bragg peak it is planned to test this chamber at a ^{12}C-beam at the GSI in Darmstadt.

V. CONCLUSION AND OUTLOOK

Prototypes of liquid ionization chambers with two and three-dimensional read-out have been developed and sucessfully tested in beams of ionizing particles.

In a prototype ionization chamber for on-line monitoring of dynamic radiation fields, high currents could be observed for purified liquids. Using a parallel read-out of a 20×20 matrix, geometric structures of radiation fields of a multileaf collimator could be resolved within sub-second time intervals.

All liquids investigated in this article presented a certain dose rate dependence. This may be considered as a disadvantage with respect to the planned monitor function. But the dependence of the measured current on the dose rate can be described with a monotone increasing function and the inverse function can be calculated. However, if the monitor concept as outlined in section II-D is being applied, a known dose rate effect can be well included in the pre-calculation of the monitor values of each pad and at each time.

Presently, new chambers with higher spatial resolution are developed for both, two and three-dimensional read-out.

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