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On-line Monitoring of Fluence Distributions and Imaging of Scanning Ion Beams

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Abstract: In this paper we describe the design of an ion beam monitor developed to control irradiations of biological samples with ions at GANIL (Grand Accélérateur National d'Ions Lourds). This device can be used as an on-line monitor to provide transverse fluence distributions for active scanning ion irradiations. It can also be used as an interceptive beam imager to provide beam profiles or fluence depth distributions. A prototype of the monitor has been tested at GANIL with five different ion beams, having intensities from 10^4 to 10^9 ions per second. Real time transverse fluence distributions have been obtained with a 1mm spatial resolution.

Keywords: Radiobiology, Radiation therapy, On-line monitor, Fluence maps, Real time ion beam imaging.

Main Text:

INTRODUCTION

The use of ions for cancer therapy with radiation is more and more used but still needs improvements. In this context, radiobiology experiments are carried out at GANIL (Grand Accélérateur National d'Ions Lourds) to investigate ion induced effects on cells (DNA

lesions, cell survivals and others [1]). During these experiments, very different biological samples are irradiated with scanning ion beams. The diversity of these studies that concern small rodents, cells, plasmids, DNA and proteins makes doses and doserates span over a very wide range. Presently, the dosimetry is based on the monitoring of the total ion current using the X-ray emission by a metallic thin foil interposed on the beam. This emission is calibrated using CR-39 track-detectors and conventional medical ionization chambers. The homogeneity of the field can only be checked off-line by using CR-39 plates or radiographic films. Obviously, heterogeneities in the radiation field induce a loss of accuracy of the dose delivery and affects the accuracy of the obtained results. Therefore, a beam monitor able to provide an accurate on-line fluence map for each sample irradiation has been developed within the framework of a collaboration between GANIL, LPC Caen (**L**aboratoire de **P**hysique **C**orpusculaire de Caen) and CIRIL (**C**entre **I**nterdisciplinaire de **R**echerche **I**ons **L**asers). The monitor has been designed within radiobiological beam experiments specifications:

- o Two high energy beams: ^{13}C (95A.MeV) and ^{84}Kr (60A.MeV).
- o All ions from carbon to neon with energies around 10A.MeV.
- o Fluence from 10^4ions/cm² to 10^{11}ions/cm².
- o Beam intensities from 10^4 to 10^9ions per second.

A beam monitor prototype named IBIS (**I**on **B**eam **I**nspection **S**ystem) has been built to meet these experimental conditions and to provide real time fluence maps. It can also be used as an interceptive beam imager.

In the following section, the design of IBIS and its calibration methods are described. The results concerning fluence maps and beam imaging are reported in the last section.

DESIGN AND METHODS

1 - Beam delivery system at GANIL

2

At GANIL, the radiobiology experiments are held in the D1 experimental area. Two beam lines are available: the first one delivers high energies ions (up to 95A.MeV) while the second one delivers ions with medium energies (~10A.MeV). The beam is pulsed at around 12.5MHz [2], which corresponds to one ion bunch every 80ns. Each bunch can contain between 0 and ten or so ions. A variable size rectangular cross section irradiation field is created by scanning the beam spot within two orthogonal directions. Figure 1 shows the details of this beam scanning:

- o Two sweeping magnets create the magnetic fields that control the two directions beam deviations (horizontal and vertical).
- o These magnetic fields follow triangular periodic time structures. The frequencies are 3Hz for the vertical deviation and 350Hz for the horizontal one.
- o The magnetic fields amplitudes (B_{x_max} and B_{y_max}, given in bins) determine the irradiation field size, which can reach a maximum size of 6cm × 6cm.

Figure 1.

2 – Fluence maps reconstruction with the prototype IBIS

Taking into account this beam delivery method (the beam spot scanned over the irradiation field), fluence maps are obtained by two simultaneous measurements performed at regular time intervals: the number of ions that crossed the biological samples and the corresponding beam spot position. For this purpose, an ionization chamber set on the beam line, between the beam exit and the biological samples, provides an ion rate measurement while two Hall effect sensors set near the sweeping magnets record the magnetic fields values and provide a beam spot localization.

a - The design of the ionization chamber

The ion rate measurement is performed by an air operating parallel plate ionization chamber. Since this detector is dedicated to perform an online control, its total thickness has to be as small as possible. Figure 2. shows a scheme and a picture of this detector: the ionization chamber is made of five 2.5µm thickness metallized mylar electrodes, with an active area of 10cm × 10cm. The thickness of each air gap is 3mm. Thus, the total water equivalent thickness is 30µm. An electric field is generated by polarizing two of the five electrodes with a high voltage, while the two external ones are connected to the ground.

Figure 2.

The typical high voltage applied is -3kV, in order to maximize the drift velocity of the ions in the chamber and thus to prevent recombination. Figure 3. shows a measurement of the ionization chamber integrated output current (*IC data*) as a function of the applied high voltage. All the measurements were performed with a constant intensity of 2.10^6ions per second, the high voltage ranging from -100V to -3kV. The output current integration time is 20µs. As shown in figure 3., with a low voltage, the integrated output current is not proportional to the incident number of ions because of the recombination of ions. With an absolute value of the high voltage higher than 2kV, all the ion pairs reach the measurement electrode within the measurement duration (20µs) and the output current becomes constant. Taking these results into account, the measurements will be performed with a -3kV supply voltage and a 20µs integration time.

Figure 3.

In these conditions, the integrated output current measured is directly proportional to the number of incident ions that crossed the detector during the integration time. In order to have an absolute ion rate measurement, we just have to determine the proportionality coefficient between the integrated output current of the ionization chamber and the number of incident ions. This is performed during a calibration step, which is detailed in the third section.

b – The Hall effect sensors

The Hall effect sensors are used to obtain the beam spot position by measuring the values of the magnetic fields every 20μs. As a matter of fact, each couple of values of the magnetic fields corresponds to a unique deviation of the spot and thus to a unique position on the irradiation field. This measurement is performed using a commercial linear output magnetic field sensor (AD22151) which provides an output voltage proportional to the magnetic field applied perpendicularly to its surface.

The beam line elements that determine the size and location of the irradiation field are displayed on figure 4. Two steerers control the deviation of the beam spot position when the sweeping is off (x_0, y_0). Then, the two sweeping magnets control the size of the irradiation field created by the beam spot scanning. The relation between the magnetic fields values (B_x and B_y) and the absolute position in the irradiation field (x,y) is linear so that four coefficients (two per sweeping direction) are needed:

$$x = x_0 + k_x \times B_x \qquad \text{and} \qquad y = y_0 + k_y \times B_y$$

The values of these four coefficients x_0, y_0, k_x and k_y have to be determined during a calibration step, detailed in the third section.

Figure 4.

3 – Calibration of the beam monitor

As shown in the previous section, two calibration steps are needed: the calibration of the ionization chamber and the calibration of the magnetic fields.

a – Ionization chamber calibration

The output current of the measurement electrode is integrated and then sampled to create an output data ($IC_{current}$) proportional to the total amount of charges collected on the electrode and thus, to the number of ions (N_{ions}) that crossed the ionization chamber:

$N_{ions} = k_{IC} \times IC_{current}$. The goal of this calibration step is to find the proportionality coefficient

k_{IC}. To measure the number of ions N_{ions} we use a liquid scintillator, coupled to a photomultiplier tube (PM tube), placed behind the ionization chamber on the beam line, as shown on figure 5.. The scintillator ("Ready Safe", from Beckman Coulter) has been chosen for its high scintillation efficiency. The entry window of the scintillator chamber is made of a 25µm thickness Mylar foil and a 10µm thickness Aluminum foil. The role of the Al foil is to screen the scintillator against external light. The thickness of the scintillator is 4cm, in order to stop the ions (the maximum range in water for ion beams used by radiobiologists at GANIL is 2.5cm). A circulation of the liquid scintillator prevents local modifications of scintillating properties due to irradiation.

Figure 5.

The intensity of each light pulse produced in the scintillator and thus, the amplitude of each PM tube output electrical pulse are proportional to the number of ions in each ns bunch. Figure 6. shows an oscilloscope spectrum of the PM pulses recorded during a few minutes. For this recording, the beam intensity was high enough (around 10^7ions per second) to have between 0 and typically 4 ions per bunch. We can see that the distribution of the amplitudes of these pulses allow an absolute counting of the number of ions per bunch by a comparison to given thresholds. Thus, the PM pulses are digitalized by the data acquisition system in order to compare their amplitudes to eight numerical thresholds and count the absolute number of ions for each bunch between 0 and 8.

Figure 6.

The absolute number of ions counting and the measured ionization current allow a determination of the calibration coefficient k_{IC}. This calibration coefficient depends on the beam characteristics (type of ion and energy). As a matter of fact, the number of charges created in the ionization chamber per incident ion is directly proportional to the quantity of

energy lost in the detector by this ion, and so, to its linear energy transfer. Thus, this calibration step has to be done before each experiment.

The linearity of the ionization chamber was checked against the absolute counting. The intensities tested range from 10^5 to 10^7 ions per second. The results are displayed in figure 7., showing the ionization chamber measurements (in arbitrary units) as a function of the absolute PM counting.

Figure 7.

b – Position calibration

The goal of this calibration step is to find the relation between the magnetic fields values and the corresponding beam spot positions on the irradiation field (coefficients x_0, y_0, k_x and k_y mentioned previously). This calibration is performed by using a plastic scintillator stopping the beam. The light emitted by the scintillator is viewed by a telecentric lens (Sill Optics S5 LPJ 1835) coupled to a photon counting CCD camera (Roper Scientific Cascade). As shown in figure 8., a mirror is placed after the scintillator in order to image the transverse distribution of the light produced in the scintillator.

Figure 8.

Figure 9. shows the transverse distribution measured by two different ways:

- o The left hand side 512×512 pixels distribution is obtained with the imaging device presented previously. The quantity of light created in the scintillator is reported as a function of the absolute position.

- o The right hand side distribution is obtained by reporting the ionization chamber measurements ($IC_{current}$) as a function of the two Hall effect sensors measurements (horizontal and vertical magnetic fields values, B_x and B_y).

As these two transverse distributions represent the same irradiation field size and location, we can use the boards of the fields to obtain four couples of points: (x_1, B_{x1}), (x_2, B_{x2}), (y_1, B_{y1})

and (y_2, B_{y2}). These couples are used to calculate the values of the calibration coefficients x_0, y_0, k_x and k_y.

Figure 9.

c – Beam spot shape

After these calibration steps, the fluence distributions are reconstructed by reporting the number of ions measurements as a function of the beam spot positions. With the 20µs integration time, a 350Hz horizontal sweeping frequency and an irradiation field size of 6cm $\times$ 6cm, we get a measurement point every 0.84mm. Nevertheless, the size of the beam spot is larger than this resolution (typically 5mm $\times$ 5mm). Thus, the beam spot shape has to be determined in order to be taken into account during the fluence map reconstruction. This step is achieved by imaging a beam spot with a plastic scintillator and the CCD camera, set as in the position calibration step. Figure 10. shows the 512$\times$512 pixels image of the spot obtained with an Argon beam at 95A.MeV. We see that this beam spot can not be approximated by Gaussian profiles. Thus, the real shape has to be imaged to get reliable fluence maps.

Figure 10.

4 - Data acquisition system

A fast digital data acquisition system has been developed specifically for the prototype IBIS. This acquisition system is an adaptation of a fast digital acquisition system developed at LPC Caen named FASTER, for **F**ast **A**cquisition **S**ys**T**em on **E**thernet Netwo**R**k [4].

As shown in figure 11., the ionization chamber "IC" and the Hall effect sensors "HES" are connected to a numerical board containing an FPGA. The PM tube coupled to the liquid scintillator, "Calib", is directly connected to a second one. The FPGA are then performing the specific data processing of the detectors output signals:

o The output current of the ionization chamber is integrated and sampled every 20µs.

o The output voltage of the sensors are sampled every 20µs.

- The amplitudes of the PM pulses are detected and compared to the eight numerical thresholds for absolute number of ions counting during 20µs.

These boards are connected to the acquisition personal computer by a Gigabyte Ethernet transmission. Data are then stored and analyzed with a home-made software coded with LabWindow software. The data acquisition rate is then 50kHz with no dead time.

Figure 11.

RESULTS AND DISCUSSION

IBIS has been tested with five beams at GANIL: Ne (13.7A.MeV), O (8.37A.MeV), C (9.07A.MeV and 11.12A.MeV) and Ar (95A.MeV).

1 - Fluence maps

The fluence maps are reconstructed by a two steps process:

- The numbers of ions measurements are plotted as a function of the corresponding beam spot positions measured by the Hall effect sensors. This distribution is not representing the real fluence distribution because the distance between two measurement points (0.84mm) is too small compared to the beam spot size.
- The beam spot image is convoluted over this previous map to obtain the real fluence distribution.

Figure 12. displays a 6cm × 6cm fluence map obtained with an argon beam at 95A.MeV during 5 minutes at GANIL. This transverse fluence distribution is not homogeneous, and the mean fluence of some area is sometimes 30% lower than the maximum fluence of the map (4.10^4ions/mm²). In this series of experiments, such patterns were always observed when changing the irradiation time, the beam intensity or the field size.

Figure 12.

These heterogeneities result from the time structure of the beam intensity. A spectral analysis of this time structure has been performed. Some constant frequencies (50Hz, 70Hz and others) seem to drive these variations. Since the sweeping frequencies are constant (350Hz and 3Hz), some areas in the irradiation field are more often irradiated than others. This is also the reason why a longer irradiation times would not lead to more homogeneous fluence distributions.

As mentioned in the introduction, without this new beam monitor, the fluence is usually controlled by off-line measurements that cannot be done systematically before each irradiation. It is then difficult to perceive the apparition of these bands and to act on the beam delivery system to eventually decree their amplitudes.

Moreover, these off-line controls can only be done within a limited range of fluence. With this monitor, the fluence maps are obtained with a 1mm spatial resolution and for a fluence ranging from 10^4ions/cm² to 10^{11}ions/cm².

By far, it is not systematically possible of getting rid of these heterogeneities by tuning the beam differently. So we will study the possibility to use this monitor to perform a feedback control of the vertical beam sweeping. Thus, homogeneous fluence distributions could be obtained and irradiation conditions would be optimized for experimentalists.

2- Beam imaging

As described before, IBIS is equipped with an imaging device for the position calibration step. This device can also be used as an interceptive real time beam imaging. For this purpose, two read out positions are used to image both transverse light distributions (position 1) and depth light distributions (position 2). These positions are schematized on the figure 13.

Figure 13.

This imaging performance of our device has been tested with a 13.7A.MeV neon beam at GANIL. Figure 14. displays the light distribution recorded by this imaging device (left hand

side), compared to the fluence distribution measured as described previously by the on-line monitor (right hand side).

<div align="center">Figure 14.</div>

These two distributions can be compared because the quantity of light created in the scintillator is proportional to the fluence. The heterogeneities of the fluence distribution can be used to check the good agreement between the beam imaging and the fluence map reconstruction performed by the on-line monitor IBIS.

The second position of the beam imager is used to obtained depth light distributions. Figure 15. displays the depth light distribution measured for a 95A.MeV argon spot. The horizontal cut of this depth light distribution doesn't fit with the Bragg curve representing the dose deposit of these ions in this scintillator. This shows that the quantity of light measured is not proportional to the dose because of the quenching effect. As far as the quenching could be studied, these light distributions could lead to 2D depth dose distributions in the scintillator and thus to perform 2D quality controls of therapeutic ion beams.

<div align="center">Figure 15.</div>

<div align="center">CONCLUSION</div>

A new ion beam monitor providing real time fluence distributions has been presented. IBIS, the prototype that has been developed and tested is based on an ionization chamber counting the number of ions per time unit simultaneously with a beam position measurement, achieved by two Hall Effect sensors. IBIS active area is 10cm × 10cm, with a total water equivalent thickness of 30μm. This on-line monitor, providing 1mm spatial resolution fluence maps, is designed to operate over a large range of intensity (10^5 to 2.10^7pps). All types of ions can be used with energies between 10A.MeV and 95A.MeV. This ion beam monitor will be set up permanently on two beam lines in the D1 experimental room at GANIL. This monitor can

also be used as an interceptive beam imager providing high resolution transverse light profiles and depth light distributions. This application could be studied and developed to perform therapeutic ion beams quality controls.

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Figures:

1. Active scanning beam delivery system in the D1 experimental room at GANIL

2. Scheme and picture of the ionization chamber of IBIS prototype

3. Recombination measurement in the IBIS ionization chamber. Argon beam at 95A.MeV with a mean intensity of 2.10^6pps

4. Creation of the irradiation field: relation between the absolute position and the magnetic fields values

5. Ion rate calibration device

6. Absolute counting method

7. IBIS ionization chamber linearity

8. Position calibration device