

INTERACTION OF THE BIOMOLECULAR IONS WITH THE ELECTRON TARGET IN THE ELECTROSTATIC STORAGE RING

Syresin E.M., Shirkov S.G.,
Joint Institute for Nuclear Research, Dubna, Russia

Abstract

A nanostructure of the radiation damages is formed at an interaction of carbon ions with DNA molecules at hadron therapy. A local interaction of the ion beam with the biomolecular structures in the human cells is defined mainly by parameters of the ion tracks. The track core is connected with ionization properties of the charged ion, its cross-section sizes are defined by the delta-electrons. The delta-electron energy varies statistically from several eV to few keV therefore they lead to substance ionization along their trajectory on a distance several nanometers from that point where they were produced.

Interaction of the delta-electrons with DNA molecules and other biological structures is one of the important mechanisms realized in process of the hadron therapy. A study of interaction of the accelerated biomolecular ions with an electron target in the electrostatic storage ring was performed for modeling of an input of the delta-electrons in processes of the hadron therapy.

INTRODUCTION

The realization of carbon therapy on a microscopic level is connected with a nanostructure of local radiation damages produced along trajectories of ions with a characteristic cross dimension of a few nanometers and a root-mean-square distance between the damages several hundred nanometers (Fig. 1), covering the structure of DNA molecules in the tumor cells with a probability around of 80%. The arising two-strand breaks of DNA molecules are irreversible because of high linear energy transfer (LET) for particles stopped in the tumor, while the structure of radiation damages in normal tissues at low LET ensures less than 10–20% probability of complications in these tissues, producing damages (predominantly single-strand DNA breaks) that allow cell functioning to be restored after irradiation.

At carbon therapy the ions produce the double-strand breaks of DNA molecules by the direct ionization. The delta-electrons are formed also at this ionization. It leads to additional DNA breaks along the electron trajectories. As a result, the radiation damages arise in the region of ion track with the lateral dimensions of the order of nm comparable with the DNA transverse dimensions. Majority of the delta-electrons have energy lower 30 eV.

The interaction of the electrons with an energy of 0.5–100 eV with the biomolecular ions at a

mass of 1000–66000 a.m. accelerated up to energy of 30 keV/Z in the KEK (Japan) electrostatic ring is discussed below.

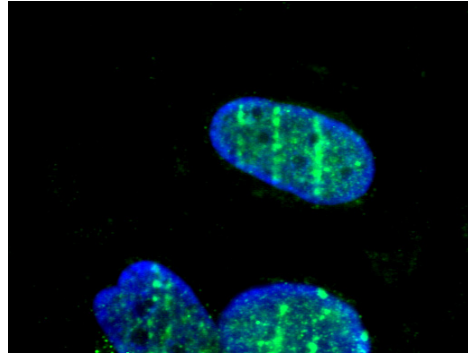


Fig.1. Photo of irradiated human cells taken at the fluorescent microscope. Fluorescent markers demonstrate nanostructured double-strand breaks of the DNA molecules caused by the carbon ions.

ELECTROSTATIC STORAGE RINGS

The magnetic rigidity $B\rho$ of the ion storage ring is determined by the ion mass M : $B\rho = (2E_i M / q_i^2)^{1/2}$, where E_i and q_i is ion energy and charge. Consequently, the biomolecular ions of proteins, amino acids or DNA ions with a mass of 10^3 – 10^6 a.m. can not accelerated in the ion storage rings with a magnetic structure. In this regard, in recent years a new class of electrostatic storage rings [1–4] was constructed. The rigidity of electrostatic ring $E\rho$ does not depend on ion mass: $E\rho = 2E_i / q_i$. These storage rings were effectively used for the formation and accumulation of the biomolecular ion beams [1–4].

The circumference of the KEK electrostatic ring is equal to 8.1 m. The accumulated current of biomolecular ions was 50–500 nA. The lifetime of biomolecular ions with masses up to 66 000 in the KEK electrostatic storage ring is 10–20 s at a pressure of $(3-5) \times 10^{-11}$ Torr. The ring acceptance corresponds to $50 \pi \cdot \text{mm} \cdot \text{mrad}$. The emittance of stored ion beam is equal to $15 \pi \cdot \text{mm} \cdot \text{mrad}$, the ion beam diameter is about 6 mm in the electron target. The relative momentum spread corresponds to 10^{-3} .

The biomolecular ions are produced in the electrospray ion source [2]. Then they are stored in the ion trap to increase by one order of magnitude the

ion beam intensity. The bunched ions accelerated up to energy of 20 keV/Z pass through the mass analyzing system with a mass-resolving power 10^3 . Finally, the biomolecular ions are injected in the electrostatic ring.

ELECTRON TARGET

The main peculiarity of the KEK electrostatic ring is related to the electron target [3,5-9] developed in KEK-JINR-NIRS collaboration. This target is applied for study of biomolecular ion-electron interaction at an electron energy of 0.5-100 eV.

The electron target design is similar to a design of the electron cooling system with a high magnetic expansion factor. The magnetic expansion factor in KEK electron target can be varied in the range of 10-100. The gun magnetic field corresponds to 1 kG, the magnetic field in the interaction region is equal to 10-100 G. The electron beam is formed in three electrode gun (Fig.2). The cathode diameter corresponds to 3.5 mm. The electron beam in the interaction region is varied in range of 11-35 mm. The length of electron-ion interaction area is equal to 20 cm. The maximum electron current corresponds to 2 mA.

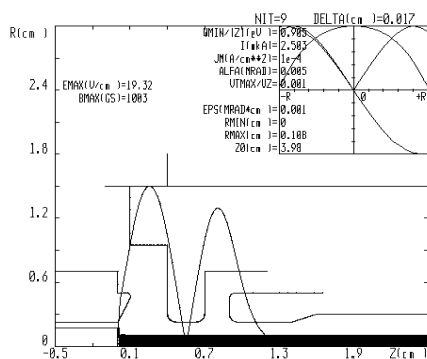


Fig.2. Electron beam formation in the three electrode gun with variable emission spot size.

The energy of accelerated electrons is defined by several parameters [6,8]:

$$E_e/e = V_{cath} + U_{min} - A/e - IR - kI/E_e^{1/2},$$

where V_{cath} is the cathode voltage, U_{min} is the potential minimum produced near the cathode surface, A is the work function of the cathode material, IR is a voltage related to the active resistance R of the emitter layer, $kI/E_e^{1/2}$ corresponds to the electron space-charge effects.

TRANSVERSE COHERENT OSCILLATIONS AT TARGET ELECTRON-ION INTERACTION

The proton lifetime reduction in KEK electrostatic ring [6] can be related to excitation of the dipole coherent oscillations produced by ion interaction

with the electron target or at the so-called electron heating effect [10].

The proper choice of working point reduces the ion-beam losses caused by the excitation of the transverse coherent oscillations. In the KEK electrostatic ring there are 4 stable working points with different amplitude functions and tunes: point A ($Q_x/Q_y=2.68/0.78$), point B ($Q_x/Q_y=3.28/0.53$), point C ($Q_x/Q_y=2.71/1.38$) and point D ($Q_x/Q_y=3.28/1.35$) [2]. The interaction of the protons with the electron target is rather weak at working point C . The ion lifetime is reduced by about 10-20% at the electron-target interaction. The simulated cooling and ion coherent-oscillation rates are equal to 2 s^{-1} and 0.5 s^{-1} for the proton beam at working point C .

The increment of the instability has a maximum at a coupling resonance $Q_x - Q_y = n$ [10]. This resonance is realized in a region around points A and D . The simulated rate of the transverse coherent oscillations is high by one order of magnitude for points A and D , compared with point C . The resonance width is of $\delta Q \approx 0.04$.

The interaction of the stored ions with a highly intensive electron target also leads to excitation of ion transverse coherent oscillations and ion lifetime reduction [6]. The resonance width of the betatron tune is rather small for the simulated ions: $\delta Q \approx 0.015$ at $I_e = 0.1 \text{ mA}$ (Fig.3) and $\delta Q \approx 0.05$ at $I_e = 0.5 \text{ mA}$. The increment of the instability has a maximum at an ion intensity of $2 \cdot 10^7$ ppp. It oscillates at a high ion intensity, which is caused by the electron drift resonances.

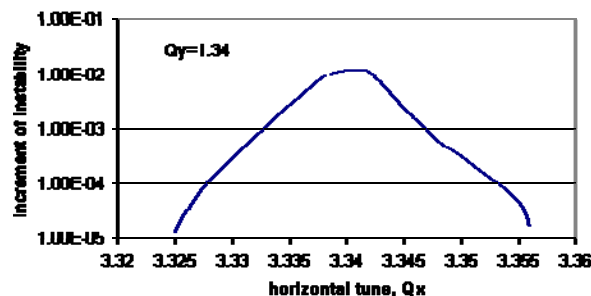


Fig. 3 Dependence of the increment of instability on the horizontal tune at $Q_y=1.34$, $I_e=0.1 \text{ mA}$, $E_e=40 \text{ eV}$, $B=30 \text{ G}$, $Z=4$, $A=1200$, $Ni=10^7 \text{ ppp}$, $\text{FWHM}=6 \text{ mm}$.

INTERACTION OF BIOMOLECULAR IONS WITH THE TARGET'S ELECTRONS

The results of biomolecular ion-target electron interactions are presented in Fig. 4 [6-7]. Fig. 4 shows the yields of neutral radicals formed at interaction of the target electrons and the ions of the basic amino argenina (mass 0.17 kDa) and ions of the peptide bradykihina (mass 1.06 kDa) with a one-dimensional structure and consisting of 9 amino acids. The interaction of electrons with biomolecular ions, became to the damage of the intermolecular bonds, resulting from the ions come off the free radicals, and whose output is recorded in the

experiment. The growth yield of neutral radicals and the relative energy of the electrons below 2 eV is associated with the contribution of dissociative recombination. For the basic amino acid Arg at electron energies greater than 2 eV yield of the neutrals increases linearly with electron energy. At the same time for bradykinin peptide consisting of 9 basic amino acids, cross section, and accordingly, the yield of the neutrals has a pronounced maximum at the relative energy of the electrons and ions of 6.5 eV. The peak in the cross section associated with breakage of peptide bonds.

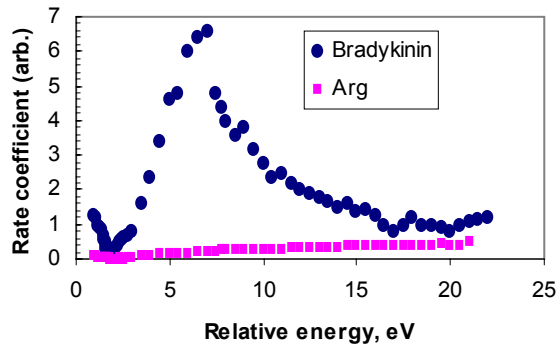


Fig.4. Dependence of the neutral radical production rate on the electron-ion relative energy.

Similar form has a cross section at the interaction of the target electrons and DNA (oligonucleotide - d (AAA)) ions. The maximum cross section of such interaction corresponds to the relative electron-ion energy of 4.5 eV (Fig. 5).

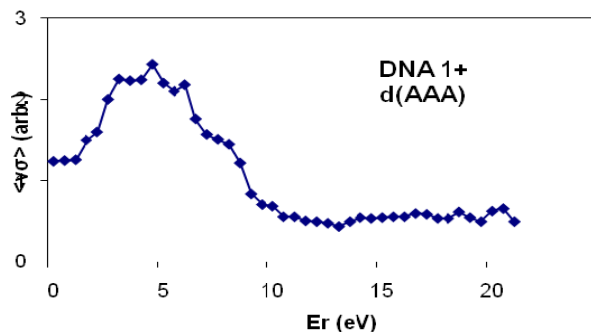


Fig. 5 Dependence of the yield of neutral radicals on relative electron-ion energy at interaction of the target electrons with the DNA ions.

ELECTRON INTERACATION WITH BIOMOLECULAR ANIONS

A collective mechanism of a plasmon excitation by DNA valence electrons at electron-DNA anion interaction is proposed in [11]. The plasma oscillations lead to break of the DNA anion bounds and the neutral particle emission. The threshold electron energy corresponds to 10 eV, when the neutral particles are

produced at electron collisions with DNA anions. The threshold target electron energy is increased almost linearly with DNA anion charge [11] (Fig. 6).

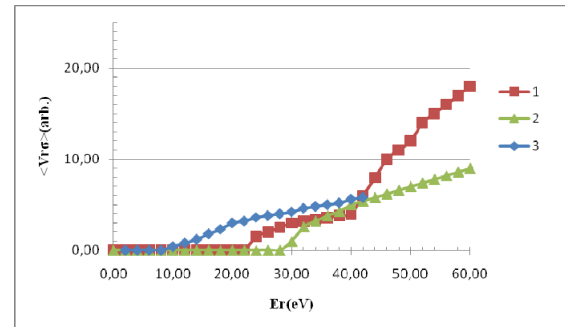


Fig. 6 Dependence of the yield of neutral radicals on relative anion-electron energy at different DNA anion charges, 1-Z=-1, 2-Z=-2, 3-Z=-3.

At small impact parameter $\rho_{\min} \approx n_v^{-1/3}$ three-body and/or collective interactions of the target electron, anion and valence electron can lead to transformation of kinetic energy of the target electron into the energy of the valence electron and excitation of the collective plasma oscillations [12,8]. The plasma oscillations brake the DNA bonds and produce the neutral molecular emission. The critical target electron energy is defined by the electron-anion interaction at small impact parameter $\rho_{\min} \approx n_v^{-1/3} \approx 1.5A$: $E_{cr} = Ze^2 n_v^{1/3} \approx Z \times 10$ eV, where n_v is the density of valence electrons.

The yield of neutral radicals corresponds to [12] $N_{rad} = (N_e N_i / \tau_{life}) \times (\rho_{\min} / \rho)^2 \approx 2$ s⁻¹, where $N_i \approx 10^7$ ppp is the number of stored anions, $N_e \approx 3 \cdot 10^6$ is the number of fresh target electrons collided with anion during its lifetime of $\tau_{life} \approx 10$ s, $\rho \approx 0.2$ mm is the average impact parameter at electron-DNA anion collisions.

REFERENCES

- [1] S.P. Moller NIM A 394 (1997), p.281.
- [2] T. Tanabe et al, NIM A 482 (2002), p.595.
- [3] T. Tanabe, K. Noda, E. Syresin, et al, EPAC 2002, p. 632.
- [4] S. Jinno et al, NIM A 532 (2004), p. 477.
- [5] E. Syresin, K.Noda, T.Tanabe, Physica Scripta, 2003, v.T104, p.185.
- [6] E.Syresin, K.Noda, T.Tanabe, in Proc. of EPAC 2004, p. 162.
- [7] T.Tanabe, K.Noda, E.Syresin, NIM A, 532, 2004, p.105.
- [8] E.Syresin, in Proc. of EPAC 2006, p.1645.
- [9] E.Syresin, S. Shirkov, III Europe-Asian Congress of Medical Physics and Engineering, 2010, v.2, p.117.
- [10] V.V.Parkhomchuk, V.B.Reva, J. of Experimental and Theoretical Physics, v. 91, N5 (2000) 975.
- [11] T.Tanabe, K.Noda, M.Saito, E.B. Starikov, M. Tateno Phys. Rev. Letters, v. 93, N.4, 043201 (2004).
- [12] E. Syresin, K. Noda, T. Tanabe, HIMAC-098, 2004.