ELECTRON STRING ION SOURCE APPLIED FOR FORMATION OF PRIMARY RADIOACTIVE CARBON ION BEAMS*

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Abstract

The ^{11}C isotopes are produced in the nitrogen gas target irradiated by a proton beam. If the nitrogen target contains 5% of hydrogen, about $4\cdot10^{12}$ methane molecules can be produced each 20 minutes. The separated methane is loaded into the ion source. The technique used for formation of radioactive carbon beams was developed and tested in the JINR electron string ion source (ESIS) Krion-2. The measured conversion efficiency of methane molecules to carbon ions is rather high; it corresponds to 17 % for C^{4+} ions. The experimentally obtained C^{4+} ion intensity in ESIS was about $2\cdot10^9$ ppp. The new ESIS-5T is under construction in JINR now at project ion intensity of $6\cdot10^9$ ppp. Accelerated ^{12}C ion beams are effectively used for cancer treatment at HIMAC. The positron emission tomography is the most effective way of tumor diagnostics. The intensive radioactive ^{11}C ion beam could allow both these advantages to be combined. It could be used both for cancer treatment and for on-line PET. Formation of a primary radioactive ion beam at intensity on the tumor target of 10^8 pps allows the cancer treatment by the scanning radiation method and on-line dose verification.

FORMATION OF HIGH-INTENSITY RADIOACTIVE CARBON ION BEAMS

Accelerated $^{12}C^{6+}$ beams at the ion intensity of 10^9 particles per second (pps) are effectively used now for cancer treatment [1]. The extracted ion intensity will be reduced to 10^8 pps at realization of scanning irradiation scheme in near future. On the other side, the positron emission tomography (PET) is the most effective tumor diagnostic.

Accelerated ion beams of the positron-emitting ^{11}C isotope (half-lifetime is 18 min) were first used at NIRS-HIMAC for cancer therapy applications [2]. The use of the ^{11}C ion beam could allow both these advantages to be combined because this beam could be simultaneously used both for cancer treatment and for on-line positron emission tomography. Verification of the radiation dose in the tumor target will be carried out simultaneously with cancer treatment.

In order to produce a ^{11}C beam for cancer therapy, the Projectile Fragmentation Method (PFM) was used at HIMAC. In this scheme the ^{7}Be target was irradiated by the accelerated primary ^{12}C beam and the maximum ^{11}C production rate was about 1% and purity was near 93%.

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To increase the intensity of primary radioactive carbon ion beams by two orders of magnitude, the ISOLDE scheme was proposed in [3]. An advantage of primary radioactive ^{11}C ion beams is the higher space resolution at PET tomography in compare to secondary radioactive beams produced in PFM.

In the ISOLDE scheme the ^{11}C isotope is produced through the nuclear reaction $^{14}N\ (p,\alpha)^{11}C$ in the target chamber filled with N_2 gas at the initial pressure of about 20 bars. The nitrogen gas target also contains 5% of H_2 to produce at irradiation $^{11}CH_4$ molecules. The proton beam from the 18 MeV cyclotron allows getting the activity of 0.06 Ci ($4\cdot10^{12}$ molecules of $^{11}CH_4$) for 20 min of irradiation with the beam current of 20 μA. A Porapac cryogenic trap is used for separation of methane $^{11}CH_4$ from N_2 gas. After the separation $^{11}CH_4$ methane molecules could be loaded into an ion source. The Electron String Ion Source [4-14] is one of the promising ion sources for generation of the positron-emitting $^{11}C^{4+}$ ion beam at the intensity of $6\cdot10^9$ pps.

ELECTRON STRING ION SOURCE

The reflex mode of the EBIS operation (ESIS mode) [6-7] is effected by using the specially designed electron gun and the electron reflector that allows a multiple use of beam electrons. The electrons do not reach the electron collector after one pass through the drift space of the source; instead, they are reflected backwards to the emitter side and then are reflected again in the vicinity of the emitter and so on. Finally, the reflected electrons can perform, depending on experimental conditions, more than 10^3 oscillations between the gun and the collector. When due to the reflections the electron density reaches a definite value, a phase transition can occur to the so-called electron string state. The string electrons are used for ion production in ESIS (Table 2) similar to the beam electrons in EBIS [5]. And in the ESIS mode it is possible to reduce the power consumption of the ESIS high-voltage system by 2 orders of magnitude and to obtain a similar effective electron density.

Now the Krion-2 ESIS is successfully used as the ion source producing highly charged ions beams for the JINR relativistic superconducting synchrotron Nuclotron [8]. This source provides a rather high pulse intensity of really highly charged ion beams, for example, Ar^{16+} - 200 μA, Fe^{24+} - 150 μA in 8 μs pulses.

The charge capacitance of the Krion-2 ion trap is $6\cdot10^{10}$ elementary charges. As was shown experimentally, adjusting the electron energy, injection time, and time of ion confinement, one can get up to 50 % of C^{4+} in the total ion beam pulse extracted from the source. So, the existing ion source Krion-2 could produce around $2{\cdot}10^9$ C^{4+} particles per pulse at an optimized ion conversion efficiency. The maximum number of C^{4+} ions produced per pulse in the Krion-2 corresponds to $4{\cdot}10^9$. The further increase of ion intensity in Krion-2 is restricted by the electron string capacity at the magnetic field of 3T. The developed in JINR new ESIS Krion-5T (Table 1) with magnetic field 5T will produce $6{\cdot}10^9$ $^{11}C^{4+}$ ions per pulse. Another advantage of the source is quite small normalized FWHM emittance of extracted beam (0.1 π·mm·mrad).

Figure 1: Electron String Ion Source Krion-2.

Table 1: Parameters of Electron String Ion Sources

Ion source	Krion-2 C^{4+}	Krion-5T C^{4+}
Electron energy, keV	3-5	5-7
Number of electrons	$6{\cdot}10^{10}$	$3{\cdot}10^{11}$
Magnetic field, T	3	5
Number of extracted ions per pulse	$2{\cdot}10^9$	$6{\cdot}10^9$
Injection frequency, Hz	0.3-1	0.3-1
Gas pulse injection time, ms	2	1
Ionization time, ms	6	2

A further increase in the intensity of the radioactive carbon ion beams is connected with the construction of the Tubular Electron String Ion Source (TESIS) [9-10] with a capacitance of the electron string and stored ions 50 times larger of Krion-2 (Table 1).

The cryogenic-based technology of accumulation and pulse injection of methane into electron string has been elaborated and experimentally proven [4,11,13]. The cryogenic cell provides pulsed injection of methane molecules with the pulse duration in the ms range. About 90% of evaporated methane molecules are injected in the ESIS working volume in 3.5 ms. (Fig.2).

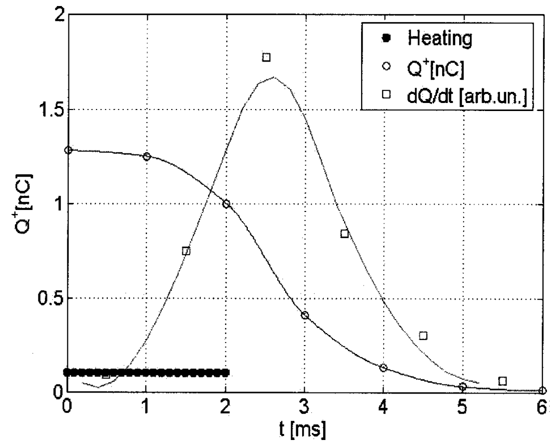

Figure 2: Total ion charge and its derivative versus start of heating and start of ion accumulation at 2 ms duration of heating pulse and ion accumulation-ionization time 10 ms.

Testing various times of methane injection and ion confinement we found out that the electron string carbon ions reach the charge state C^{4+} approximately in 8 ms. The ion charge state spectrum after 6 ms confinement is presented in Fig. 3. Then, injecting the methane molecules during 1 ms, we found out that after their confinement in the Krion-2 electron string during 5.8-6.2 ms the percentage of C^{4+} in the carbon ion charge state distribution is the highest and amounts to 53%.

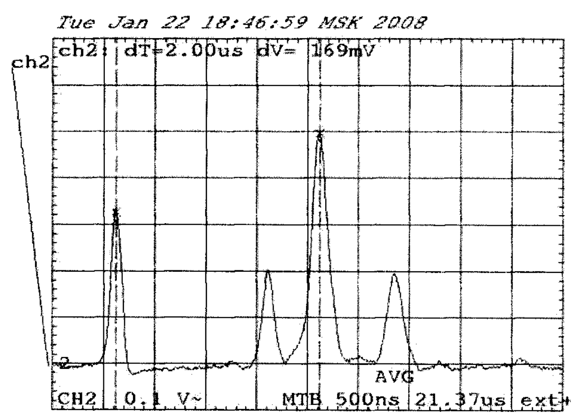

Figure 3: Spectrum of charged ions (H^{+}, C^{5+}, C^{4+}, C^{3+} pics).

Experiments with methane gas pulse injection were performed at ESIS electron energy 3,1 keV, injection current 6.4 mA and injection-extraction repetition frequency 0,71 Hz. The number of extracted ions per injection pulse corresponds to $4.6{\cdot}10^9$ that is equal to ion charge of 3 nC (Fig.4).

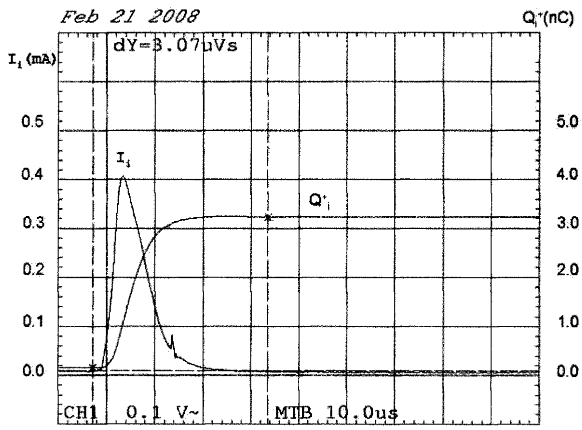

Figure 4: Total ion charge per methane injection pulse.

The methane molecules (10^{14} molecules) loaded in the ESIS per cycle are transformed in the ions during 4.9 hours with total ion charge of Q^{+}=29 μC. The ion charge spectrum contents about 38% of C^{4+} ions. The total C^{4+} charge is equal to 1.1 μC. Therefore the 10^{14} methane molecules are transformed into $1.7 \cdot 10^{13}$ ions C^{4+}, that corresponds to conversion efficiencies 17%.

FORMATION OF PRIMARY RADIOACTIVE CARBON ION BEAMS FOR HIMAC SCANNIG IRRADIATION

The radioactive carbon beams are planed to use for the HIMAC raster scanning irradiation (Table 2).

Table 2: Parameters of HIMAC Raster Scanning System with Zigzag Trajectory

Diameter of spherical tumor target, mm	120
Number of raster points	$1.4 \cdot 10^{5}$
Number of slices	63
Number of ions produced dose 1Gy	$6 \cdot 10^{9}$
Number of extracted ions per second	10^{8}
Period of injection-extraction cycle, s	30
Time of slow extraction pulse, s	20
Irradiation time at 1Gy dose, min	1.25

According to the HIMAC cancer therapy raster scanning requirements, the ion source should produce C^{4+} ion beams with the intensity of $6 \cdot 10^{9}$ particles per pulse and pulse width of 0.1 ms. Note that a limited number of methane molecules ($\sim 4 \cdot 10^{12}$) is available during each 20 minutes. At a slow speed of the HIMAC injection bump displacement of 0.8 mm/turn the small beam emittance of 2 π·mm·mrad at injection energy of 6 MeV/u permits to improve present HIMAC injection efficiency at the beam emittance of 10 π·mm·mrad by a factor of 2 and to reach injection efficiency of 60%. As a result, the project number of ions produced in the ring per injection-extraction cycle and applied for the scanning irradiation corresponds to $2 \cdot 10^{9}$ particles. Maximum number of extracted ions is equal 10^{8} pps at HIMAC raster scanning.

Table 3: Project Parameters of Primary Radioactive Carbon Ion Beam Produced at ESIS Injection in HIMAC

Methane target	
Number of produced $^{11}CH_4$ molecules	$4 \cdot 10^{12}$
Methane loading cycle, min	20
Ion source parameters	
Number of methane molecules used per pulse injection	$4 \cdot 10^{10}$
Methane conversion efficiency into ions, %	15
Number of produced ions per pulse	$6 \cdot 10^{9}$
Linac	
Linac and striping efficiency of $^{11}C^{4+}$,%	80
Injection current, μA	45
Injection emittance at 6 MeV/u, π·mm·mrad	2
Number of injection turns	30
Injection time, μs	120
Injection efficiency, %	60
Synchrotron	
Number of ions in coasting mode	$2.8 \cdot 10^{9}$
Horizontal emittance, π·mm·mrad	80
Number of accelerated ions	$2.2 \cdot 10^{9}$
Number of ions produced for scanning irradiation per injection-extraction cycle	$2 \cdot 10^{9}$
Number of extracted ions per second	10^{8}

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