DESIGN OF A NOVEL TUBULAR ELECTRON STRING ION SOURCE (TESIS)

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Abstract

The project started in 2007 is aimed at creating a Tubular Electron String Ion Source (TESIS) and to studying an electron string in the tubular geometry. The collaboration consists of JINR (Dubna) and the Russian Federal Nuclear Center (Sarov, Russia), the Manne Siegbahn Laboratory (Stockholm, Sweden), TRIUMF and the Atomic Energy of Canada Ltd. (Canada). The tubular concept of the ion source was proposed a few years ago. Preliminary theoretical estimations and numerical simulations were done, which allowed experimental realization of this project to start. The new tubular source with a superconducting solenoid up to 5 T should be constructed in 2009. It is expected that this new TESIS (Krion-T1) will meet all rigid conceptual and technological requirements and should provide an ion output approaching 10 mA of Ar^{16+} ions in the pulse mode and about 10 μA of Ar^{16+} ions in the average current mode. Having these output parameters, Krion-T1 should be an operational prototype of further TESIS sources for possible applications. Simulation results and a basic sketch of the TESIS construction is presented.

ELECTRON STRING ION SOURCE

The so-called reflex mode of Electron Beam Ion Source operation has been under intense studies, both experimental and theoretical at JINR during the last decade [1-3]. The Electron String Ion Source (ESIS) corresponding to the reflex mode of EBIS operation is based on a specially designed electron gun and an electron reflector that allows multiple use of beam electrons [1-3]. At some conditions the electron string could form that provide efficient electron accumulation with about few hundreds reflections for each electron. The electron string can be used for production of highly charged ions similarly to beam electrons. The interest in the ESIS mode was motivated by the attractive possibility of decreasing the electron beam power by a factor of 100 preserving simultaneously the same ion yield. Krion-2 ESIS has been used successfully at the injection complex of JINR synchrotron Nuclotron for production of highly charged ion beams: Ar^{16+} - 200 μA, Fe^{24+} - 150 μA in 8μs pulses (see Table 1), which were accelerated up to relativistic energies and used in physics experiments [3].

TUBULAR ELECTRON STRING ION SOURCE

The idea of using a tubular electron string ion source (TESIS) has been put forward recently [4-5] to obtain 1-2 orders of magnitude increase in the ion output as compared with ESIS (Table 1). The gain of the highly charged ion input in TESIS compared with ESIS is characterized by a ratio of tubular beam diameter d to radial beam thickness a: $N_{TESIS}/N_{ESIS}=2 \cdot d/a \approx 10\text{-}100$. The main point is that use of tubular geometry of drift tube structure allows to avoid virtual cathode formation for the corresponding amount of accumulated electrons. It was found experimentally [1-3] that the maximum number of electrons accumulated in a string was proportional to a confined magnetic field B to the third power $Q^-=aB^3$. Increases in the magnetic field from 3 T in Krion-2 to 5 T in Krion-T1 could permit about 5 times increase in the number of stored electrons and their density. The increase in the electron density at 5T reduces the ion confinement time, which determines the injection repetion frequency.

The method of the off–axis TESIS ion extraction was proposed in [4-5] to get TESIS beam emittance comparable with ESIS emittance.

Table 1: Parameters of electron string ion source

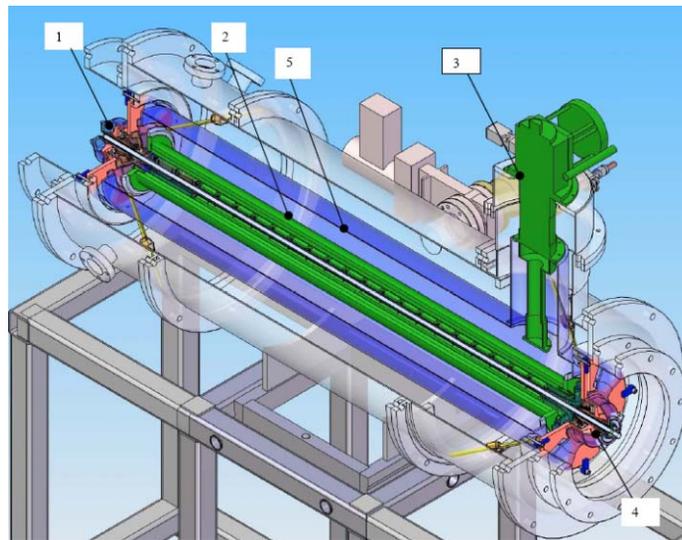| Ion source	Krion-2 Ar^{16+}	TESIS Ar^{16+}
Electron energy, keV	3-5	5-7
Number of electrons	$5 \cdot 10^{10}$	$2 \cdot 10^{12}$
Magnetic field, T	3	5
Ion current, mA	0.15	10
Pulse duration, μs	8	8
Number of extracted ions	$5 \cdot 10^{8}$	$3 \cdot 10^{10}$
Injection frequency, Hz	1	5
Average current, μA	0.15	10

Figure 1: General view of the tubular electron string ion source, 1-electron gun, 2-superconducting solenoid, 3-cryocooler, 4- reflector electrode,   5- thermal shielding at temperature of 40 K.
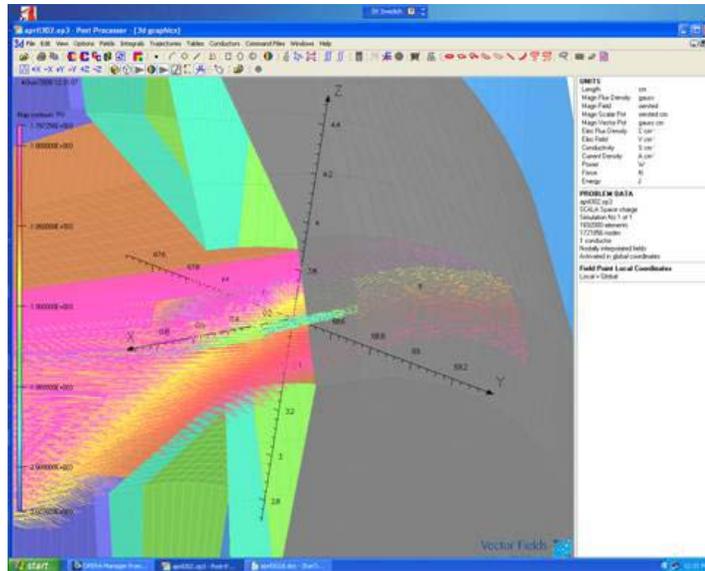

Figure 2: Plot of the ion beam (green at the center), extracted to the right direction by the negative reflector potential (grey). Electrons (red) are reflected back by this potential. This plot is a result of the Opera-3D code simulation with electron and ion beam space charges. The electrodes are cut along the extraction channel plane.

DESIGN OF TESIS

The tubular electron string ion source consists of the following systems (Fig.1): cryomagnetic, electron-optical, ion-optical, vacuum, power supplies, diagnostic and control electronics.

The parameters of the superconducting solenoid are given in Table.2. The superconducting solenoid **2** is fixed by two supports on the vacuum chamber. The cryocooler head **3** is placed at the edge of the cryostat part. The current loads, thermal shielding, superconducting keys, cooled diodes and resistors are placed between the cryocooler and the solenoid. The thermal shielding is connected with the first cryocooler section at the temperature of 4.2 K. The power of the first cryocooler section is 1.5 W. The temperature of the second cryocooler section is of 40 K. The electron gun, reflection electrodes, and other elements have temperature from room to cathode temperature.

Ultrahigh vacuum of 10^{-9}–10^{-10} Pa is the main feature of the tubular electron string ion source. This vacuum should be provided in the space between the internal and external drift tubes. Choice of the vacuum system design is dictated by a small diameter of drift tubes (internal diameter is 0.9 cm, external one is 1.5 cm) which are 120 cm long. The cryo-pumping conception was adopted for TESIS. The external pumping provides preliminary

pressure of 10^{-4} Pa and then an ultrahigh vacuum is achieved at cryosorption of surfaces cooled to temperatures of 4.2 K and 40 K. The external drift tube is cooled to 4.2 K, which permits its internal surface to work as a cryopanel on which all gases are frozen (except He, H_2). The internal drift tube is connected to the cryocooler section at 40 K. The surface of the internal drift tube works also as a cryopanel with a smaller sorbtion efficiency as compared with the external one. Different gases except He, H_2 are also frozen here. Some problems can be appeared at pumping of hydrogen. It is connected with high outgasing of hot gun surfaces and the anode reflector. A high level of outgasing is usually realized at the initial work stage and it essentially decreases with increasing operation time. The external pumping is provided only for initial operation time. The outgasing sources, the gun and the reflector electrodes are placed near the pumps on both edges of the setup and this reduces the problem at initial pumping of hot surfaces.

Table 2. Parameters of Magnetic System

Parameter	Value
Internal solenoid diameter, mm	75
External solenoid diameter, mm	103
Solenoid length, m	1.2
Maximal current, A	95.22
Number of windings per layer	2263
Number of layers	22
Total number of windings	49786
Thickness layer, mm	0.63
Current density, j/mm^2	285.1
Maximal field, T	5.0
Fr, kG/radian	2.46×10^4
$2 \times \pi \times Fz$, kG	5.68×10^3
Induction, Gn	14
Stored energy, kJ	63
Cooled mass at 4.2 K, kg	~ 50
Compound	Prepreg

Based on the computer simulation we realize the design of the electron-optical and ion-optical systems (Fig.1). The electron gun has three electrodes. The diameter of the cathode emitter is 8 cm, its width is 2 mm. Suppressing electrodes are installed to suppress emission by the appropriate voltage, applied to the electrodes, which is necessary for efficient operation in a typical pulsed mode of injection. The gap between the annular emitter and the suppressing electrodes is 0.4 mm, the slit between the suppressing electrodes has radial length 1 mm, and the cathode-anode distance is 0.5 cm. The chosen gun is an annular version of the Pierce-type gun since the slopes of the focusing electrodes are 22.5 degrees with the central magnetic flux line.

The electron reflector was chosen mirror symmetrically with respect to the solenoid center. The orifice for ion extraction is foreseen to be arranged instead of the emitter at some azimuthal position of the reflector. The reflection voltage is chosen to be a few kV lower than the cathode voltage in order to provide total reflection of the whole electron beam. The drift tube structure consists of several electrodes which are used for production of ion traps, formation of a tubular ion beam, off-axis ion extraction, and observation by means of pick-up electrodes of processes related to the electron string and ion beam formation. The ion extraction channel runs along the magnetic flux line at a definite azimuthal angle. Off-axis ion extraction was simulated with use of the Opera-3D (Scala) code. On the basis of these simulations the azimuthal width of the extraction channel was optimally chosen to be 10 degrees. The extraction channel begins in the uniform magnetic field region and consists of several electrodes which follow the shape and size of the corresponding magnetic flux lines up to B/20. Azimuthal ion migration in a uniform field region naturally occurs due to drift motion of ions in the longitudinal magnetic and radial electrical fields. When ions approach the beginning of the extraction channel, they are reflected back to the uniform field region by the applied positive voltage, except those ions which are captured in the extraction channel. Ions in the extraction channel are azimuthally confined due to the potential well created everywhere along the extraction channel in the azimuthal direction. Moreover, ions are accelerated towards the extraction orifice in the weak magnetic field due to the gradual decrease in the applied potentials along the extraction channel. It was proven in various simulations that ions could be accelerated to 2·Z keV in the extraction channel without disturbing the electron beam. The electron reflector mounted at B/20 reflects electrons and extracts ions (Fig.2). The extracted ion beam penetrates the orifice in the reflector placed at the same azimuthal position as the ion extraction channel. The extracted ion beam has an ellipsoidal shape 0.2 cm in the radial and 0.8 cm in the azimuthal direction. This azimuthal size is the minimal one allowed by the applied voltage on the extraction electrodes at the chosen azimuthal size of the extraction channel.

ACKNOWLEDGEMENTS

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