PECULIARITIES OF ELECTRON COOLER OPERATION AND CONSTRUCTION AT ULTRA LOW ENERGY IN AN ELECTROSTATIC RING

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Abstract

Few projects of electrostatic rings with electron cooler are discussed now. Electron cooling at low electron energy of 10 eV was realized at the KEK electrostatic ring. The electron cooling permits to suppress the ion multiple scattering on residual gas atoms and allows increasing the ion lifetime. Peculiarities of an electron cooler operation and construction at ultra low energy in an electrostatic ring are considered. The cooler gun operation regime is cardinally changed at a reduction of the electron energy to a value comparable with a cathode work function. A virtual cathode and ohmic resistance of cathode emitter give an input in beam formation at ultra low energy. Effective electron cooling of heavy atomic and bimolecular ions at mass of 100-1000 can be reached at a small diameter of 1 mm and a high magnetic expansion factor of 10-1000. The electron cooler construction has traditional design in KEK electrostatic ring. The cooler construction can be simplified at a small circumference of electrostatic ring. Straight cooler schemes without toroidal magnets permit to reduce ring space required for electron cooler.

INTRODUCTION

The electrostatic storage rings are used to store ions of different masses when the ion kinetic energy and the charge state values are the same [1]. The ions of different masses and charge states have been stored in the electrostatic storage rings at Aarhus [1], KEK [2-3] and Tokyo Metropolitan University [4]. Few new projects of electrostatic rings are under realization now [5-6].

In order to study the electron-ion collisions in the KEK electrostatic ring, a merging electron-beam target was constracted [3,7]. The electron target is also used as an electron cooler [7]. The electron cooling permits to compensate the multiple scattering ions at an interaction with residual gas atoms and to increases the ion lifetime by several times [7-11]. The layout of the KEK electron target/cooler has the same structure as an electron cooler with an adiabatically expanded electron beam [3, 7]. Electrons are emitted from a thermo-cathode with a diameter of 3.5 mm in a solenoid field of 1 kG. The electron beam is adiabatically expanded to a diameter of 11-35 mm in a magnetic field of 100-10 G.

The peculiarities of electron cooler/target operation and construction is related to a low electron energy of 50 mV- 100 V and short length of cooler/target section.

GUN OPERATIONS AT ULTRA LOW ELECTRON ENERGY

Extremely low electron energy of 50 meV-100 eV is main peculiarity of the electron target/cooler in an electrostatic ring. The electron energy is defined by five effects [10]: $E_e/e=V_{cath}+U_{min}-A/e-IR-kI/E_e^{1/2}$, where U_{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 and last term $kI/E_e^{1/2}$ corresponds to the electron space-charge effects. At an electron energy of 5-10 eV and a beam current of 10-100 μA all disscused effects give input of the same order of magnitude. All these constants are determinated from dissociative recombination of molecular ions [7, 11] in which the neutral-particle production rates have maximum at the zero relative energy between the electrons and the ions. Also these constants can be finding from the gun Volt-Ampere characteristics [10].

The gun [10, 12] of the KEK electrostatic ring consists of the cathode, the Pirce electrode with a variable voltage, the anode and ground electrode (Fig.1). It permits to combine both electron cooler/target functions. The variable voltage of Price electrode [13] permits to change shape and spot size of emmitted beam. The electron current is defined by accelerating voltage U_{accel} and gun perveance P_{gun}: $I=P_{gun}U_{accel}^{3/2}$. The real accelerating voltage U_{accel} is determinate by nominal cathode–anode voltage U, value of potential minimum U_{min} and voltage of emitter layer IR: $U_{accel}=U+U_{min}-IR$. A difference of accelerating and cathode-anode voltages $\Delta U=U_{accel}-U$ versus beam electron current I at cathode voltage of U_{cath}=30 V and gun perveance of P_{gun}=1.9 μA/V$^{3/2}$ is shown in Fig.2 [10]. The value of emitter resistance layer can be extracted at a high electron current from Fig.2 and then the minimum potential U_{min} can be fined.

The gun operation is cardinally changed at a cathode voltage of $U_{cath} \approx$ 2-3 V, when this value is close to the cathode emitter work-fuction $A/e \approx$ 2.8 V. The electron energy in this case corresponds to $E_e \approx$ 0.2-0.3 eV and it is comparable with cathode electron temperature $T \approx$ 0.1 eV. The emitted electron current is fast reduced at a cathode voltage reduction for a fixed cathode - anode voltage (Fig.3).

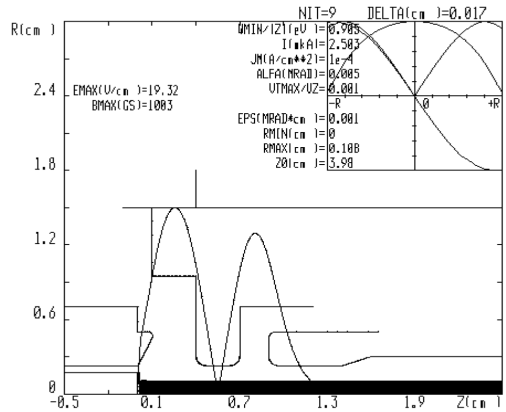

Fig. 1 Beam formtion in the electron cooler gun of the KEK electrostatic ring [10].

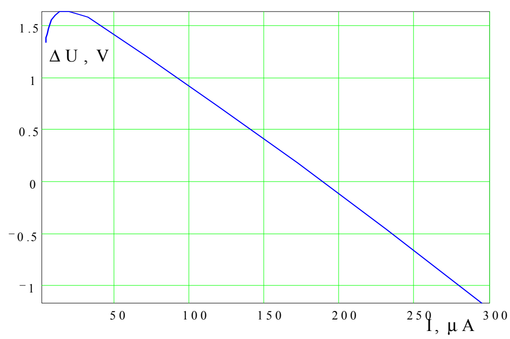

Fig. 2 Difference of accelerating and cathode voltages versus the beam current in the KEK electrostatic ring gun [10].

The maximum electron current is defined by electron energy of the axis electrons and perveance of the cooler vacuum chamber of P_{cham}≈5-10 μA/$V^{3/2}$. The maximal electron current corresponds to 1 μA at electron energy of few hundred meV for the KEK electron gun.

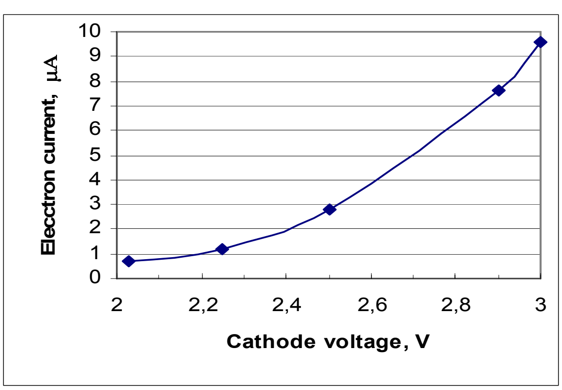

Fig. 3 Dependence of electron current on cathode voltage at fixed accelerating cathode-anode voltage of 4 V [12].

The reduction of cathode emitter spot size permits to optimize the cooling time. The beam current behaviour at negative Pirce electrode voltage is given on Fig.4. The saturation of electron beam current realized at a high cathode-anode voltage is defined by the virtual cathode between anode and ground electrode. The reduction of electron current at small cathode-anode voltage and negative Pierce electrode voltage is related to reduction of emitted spot size and decrease of electron energy to level of 50 meV.

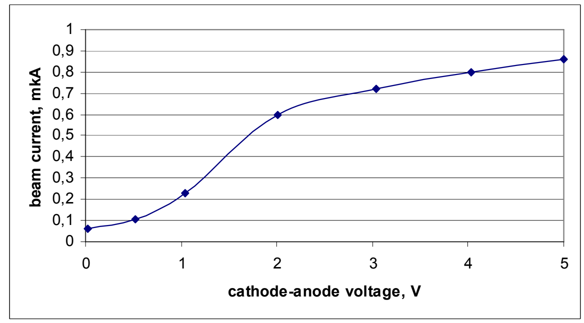

Fig. 4 The dependence of beam current on cathode-anode voltage for KEK electrostatic gun at cathode voltage of U_{cath}=2 V, Pierce electrode voltage of U_{Pierce}= –2 V [10].

STRAIGHT COOLER/TARGET SCHMES

The structure of the electron cooler/target of the KEK electrostatic ring is same as an ordinary adiabatic expansion cooling device. The cooler/target length corresponds to 20 cm at KEK circumference ring of 8.1 m.

A straight cooler was used in [14] at H^- cooling by electrons with an energy of few tenth eV. The electron gun in this cooler is displaced from the H^- beam axis. The electron trajectories coincident with ion ones in cooler section caused by electron drift motion inside two plates with transverse electric and longitudinal magnetic fields [14].

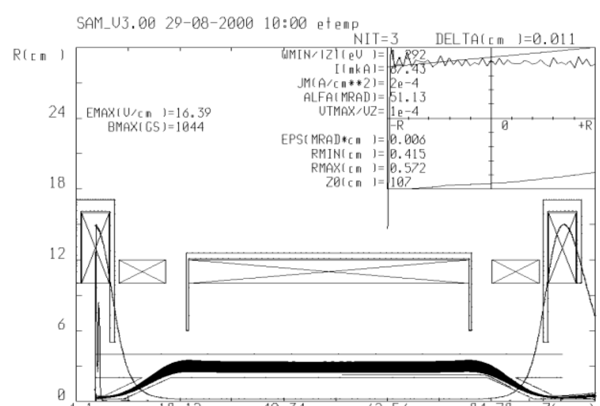

Fig. 5 Scheme of straight cooler/target with tube shape electron beam [8].

A tube shape electron beam [8] is proposed for electron cooler/target in a low energy storage ring. The tube shape electron beam is formed in a gun with tube shape cathode placed in a strong magnetic field. The tube shape beam is especially attractive for the multi turn injection or for the single turn injection when the ion horizontal beam size is larger by several times than the vertical one. The tube shape electron beam can be easily formed at strong magnetic expansion factor of 50-100. The radial (Fig. 6) and azimuthal angles correspond to several mrad in central part of electron target/cooler at a length of 60 cm.

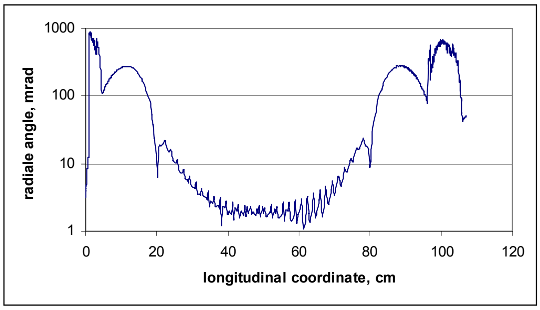

Fig.6 The dependence of radial electron angle relatively to cooler axis on longitudinal coordinate at I_e=67µA, E_e=1.2 eV, H_{gun}=1040 G and H_{cool}=14 G.

ELECTRON COOLING

The proton lifetime is increased by a factor of around 2 with a velocity-matched electron beam at energy of 10.9 eV, an electron current of 202 µA and an magnetic expansion factor of 33 at the KEK electrostatic ring (Fig. 7) [7]. This clearly indicates that ions are cooled in the transverse direction.

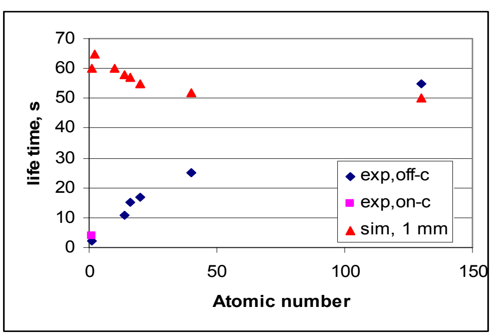

Fig. 7 Dependence of the ion lifetime on the atomic number, experiments [7] are given for cathode diameter of 3 mm.

According to BETACOOL simulations the proton lifetime also increases by factor 2 at application of KEK gun with cathode diameter of 3 mm.

A reduction of the cathode diameter to 1 mm and the transverse temperature to 1 meV permits to increase by 3-4 times the simulated lifetime of ions with an atomic number of $A/Z \approx$ 20-40 and an ion energy of 20 keV [9-11].

ELECTRON INTERACATION WITH BIOMOLECULAR ANIONS

An interaction between DNA and electrons is great inters for radiation damage and radiation therapy.

A collective mechanism of a plasmon excitation by DNA valence electrons at electron-DNA anion interaction is proposed in [15]. 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 [15]. The threshold target electron energy is increased almost linearly with DNA anion charge and it is agreed with a value of $E_e \approx Z\hbar\,\omega_p \approx 10 \cdot Z$ eV, where Z is the anion charge, ω_p is the plasma frequency of the valence electrons [15].

At small impact parameter 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. The plasma oscillations brake of DNA bonds and produce the neutral molecular emission. The rate of neutral emission is estimated as several events per second. The estimated threshold electron energy is proportional to anion charge Z at collective interactions [16]:

$$E_e \approx Ze^2 / 2\pi\varepsilon_0 l_{DNA} \cdot \left[\ln\left(l_{DNA} / r_d\right) + 1\right] \approx 6 \cdot Z \text{ eV},$$

where l_{DNA}≈30 A is the DNA size, r_d≈2A is the Debuye radius.

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