Experimental Studies of Discharge under Magnetic Field for the Electron Gun Design of the ACR Electron-Cooler

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Abstract

An electron cooler (EC) device will be applied in the Accumulator-Cooler Ring (ACR) of the Multi-Use Experimental Storage rings (MUSES) complex of the Radio Isotope Beam Factory (RIBF) project at RIKEN. A high cooling efficiency for injected ion beam with high energy is required for the EC device. A strong superconducting (SC) magnetic field of 4T is necessary at the gun section for an adiabatic expansion method in order to obtain short cooling time, while the specified electron energy is up to 250keV. No other EC devices in the world have been operated in an SC magnetic field with a few hundred kV electric field. Some technological difficulties have been encountered in the course of the design and research activities, one of which is that D.C. discharge limit appears to decrease in a high magnetic field. The discharge in the magnetic field has not studied well both analytically and experimentally. A test bench with a direct-cooled SC magnet was constructed for experimental studies and electron beam orbit analyses were performed to investigate the phenomenon.

1 Introduction

An EC device is used in the MUSES-ACR whose ion energy is from 60 to 400 MeV/u corresponding to the electron beam energy from 30 to 250keV. The EC device applies a scheme of adiabatic transverse expansion [1] for high cooling efficiency. Since the solenoid field at the central section is 0.2T and the optimum expansion factor is estimated as 20, the magnetic field at the gun section is 4T in the SC region.

Compact design of the gun system is favorable for the SC magnet but makes vacuum conductance worse and gaps between electrodes narrower so that discharge breakdown is easy to occur. The compact design is particularly important for the ACR-EC because it is planned to use a direct-cooled SC magnet with easy operation and easy maintenance.

A few EC devices with SC magnets have already been successfully operated in the world, whose electron beam energy is less than 100keV; rather small.

Under a magnetic field, an electron moves along the magnetic field line with circulating around it. Though the complex motion is thought to give the influence to the discharge limit and thus to be important to design the electrodes configuration and the insulation of the gun, only few experimental or analytical studies have been reported.

A discharge test bench has been constructed with a direct-cooled SC magnet yielding up to 4T field. While the experimental research has been performed with the bench, the electron orbit trace has been calculated.

2. Test Bench for Discharge in Magnetic Field

Purpose

An experimental test bench has been constructed in order to research the behavior of the discharge limit at a simple gap or at an insulator gap with various magnetic field values. The atmosphere around gaps is vacuum or SF6 gas. The maximum magnetic field is 4T, same as one at the gun section of the ACR-EC devices.

Structure

The discharge test bench is shown in Fig.1.

A stage for test piece (T.P.) setting is located from the lower side of a vacuum vessel. A lower T.P. is mounted at the stage with a square-shaped electrode-holder between them. A high voltage feed-through comes from the upper side of the vessel, whose end is a connection holder of an upper T.P. support. A corona shield with a cylindrical shape is placed between the feed-through and the holder to prevent an unexpected discharge. For attaching a T.P., the upper T.P. support has the rectangular metal plates of the same dimension as the lower T.P. stage.

In order to simplify the job for T.P. exchange, these two supports and two T.P.'s are constructed outside the vessel and connected each other with insulator support bars. And all of them are mounted in the vessel at a time.

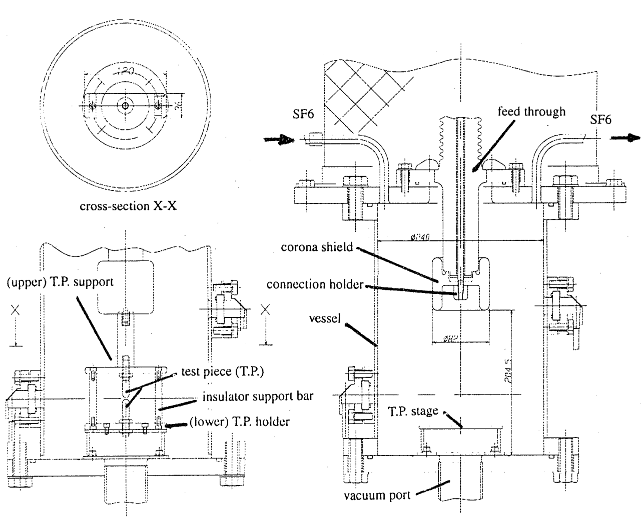

Fig.1 A Discharge Test Bench

Each T.P., which is used in fundamental experiments and discussed in this paper mainly, has a spherical end. In the further tests for a surface discharge along an insulator, a ceramic gap or an accelerating tube was mounted and tested.

The lower T.P., its stage and the wall of the vessel are grounded. The feed-through, the upper stage and the upper T.P. are insulated against the vessel wall and are given high voltage by a DC 100kV power supply.

The vessel has a vacuum pumping unit and also an SF6 filling unit. In case that an accelerating tube is set between two stages, it is possible to evacuate the tube independently. It enables to simulate the atmosphere of the accelerating tube in the actual operation; vacuum inside and SF6 outside.

A direct-cooled SC magnet is placed around the vessel, which produces a magnetic field up to 4T.

3. Experimental Results and Consideration (1)

Fundamental Experiments

As the first experiments, two simple T.P.'s with a spherical end of a 5mm radius were set with a 1.5mm gap. In vessel it is vacuum or with SF6 gas of 2.0 or 3.3kg/cm^2. The vacuum level was $3.3*10^{-6}$ Torr. The results are shown in Table 1.

The discharge limit value was measured three times at each magnetic field strength. The polarity of the high voltage at the upper electrode was positive.

The limit in SF6 gas didn't depend on the magnetic field and was 31-37 kV in 2.0kg/cm^2 and 45-50 kV in 3.3kg/cm^2.

In vacuum, however, unexpected results were observed. Without a magnetic field, the discharge limit was 54-57 kV, which was higher than one in SF6 gas. However in the magnetic field, even if it was only 10mT, the discharge limit was strongly reduced to 1.3-1.6kV. The phenomenon was reproducible and the limit was slightly reduced to 0.9 kV for higher magnetic field up to 4T.

Some discussions and considerations were done for analyzing the unexpected results.

Table 1 D.C. Discharge Limit between 1.5mm Gap with a Magnetic Field
(T.P.: 5mm radius spherical end; HV polarity = positive)

atmosphere	mag. field(T)	voltage limit(kV) 1st	2nd	3rd	atmosphere	mag. field(T)	voltage limit(kV) 1st	2nd	3rd
Vacuum 3.0*10E-6 (Torr)	-4	1	1	1	SF6 2.0kg /cm2.abs	-2	36	37	34
	-2	1	1	1		-1	37	33	37
	-1	1	1	1		-0.5	37	31	37
	-0.5	1.1	1	1		0	38	37	36
	-0.1	1.1	1.1	1		0.5	35	32	33
	-0.02	0.9	0.9	0.9		1	35	33	33
	-0.01	1.3	1.3	1.3		2	35	34	34
	0	57	54	54		4	37	34	34
	0.005	53	54	54	SF6 3.3kg /cm2.abs	-2	47	46	45
	0.01	1.6	1.5	1.5		-1	46	45	45
	0.02	0.8	0.8	0.8		-0.5	50	49	47
	0.1	0.9	0.9	0.9		0	48	45	50
	0.5	1	1.1	1.1		0.5	48	48	46
	1	0.9	1	1		1	49	46	47
	2	1	1	1		2	49	49	46
	4	0.9	0.9	0.9		4	50	48	47

Discussion and Consideration (1)

Firstly it was wondered whether the discharges were occurred between two T.P.'s as expected.

In SF6 gas, the discharge limit was changed from 50 to 60 kV as the gap between electrodes was spread from 1.5 mm to 2 mm. Thus the discharge was considered to occur between electrodes.

Since scratched-like lines were observed at the upper electrode after the test in vacuum without a magnetic field, the discharge also seemed to occur between gap as expected.

On the other hand in vacuum with a magnetic field, the discharge limit was almost constant with any gap distance. Further experiments were done to find where the discharge occurred. With the same condition in vacuum with a magnetic field, the discharge limit was measured without the T.P.'s. And it was also measured without both the T.P.'s and the upper T.P. support. As a result, the discharge limit values were not changed much. All the experimental results showed the unexpected discharge in vacuum with a magnetic field was thought to occur due to the corona shield.

The next discharge tests were with negative voltage. The electrodes were same as the final test situation, where the T.P.'s and the T.P. support were removed.

The results were shown in Fig. 2. The discharge limit was more than several ten kV even in the high magnetic field up to 4T, though the limit decreased slightly as the field got bigger. The change of the polarity causes the difference of the electron behavior in the magnetic field. The analytical survey of the effects was performed with a simulation program, as shown below.

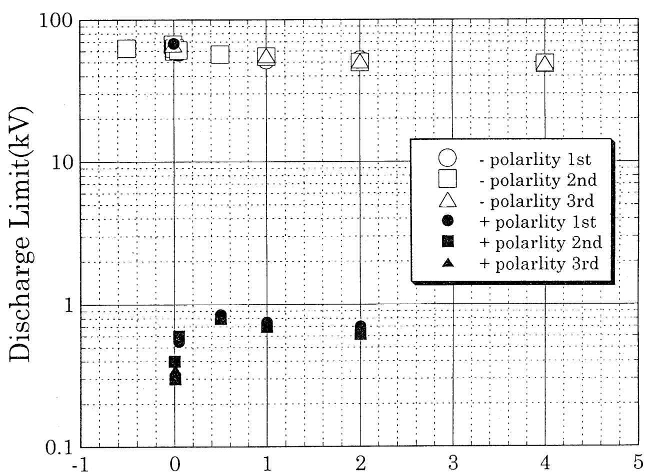

Fig.2 HV Polarity Effect on D.C. Discharge Limit in Vacuum with a Magnetic Field
(T.P.: 5mm radius spherical end; 3.3*10E-6[Torr])

Simulation Code and Condition of Calculation

Analytical research was performed to investigate the polarity effect by the simulation code "MIG", developed at Toshiba co.. The conditions of the calculations were;

(1) The high voltage feed-through of ceramics and the T.P. fixture stage were omitted to make the problem simple.

(2) Electrons were generated at the surface of the vessel or the corona shield with the initial velocity of 0.1eV.

(3) The potential was 0V at the vessel wall surface and +1kV or -1kV at the corona shield.

(4) The effect of the collision of electrons and molecules of residual gas was not taken into account.

Calculation Results

The electron orbits were calculated in a few cases, some of which are shown in Fig.3.

<Case 1> B=10Gauss, V=+1kV

The emitted electron from the vessel wall surface does not arrive at the corona shield because of the magnetic field and runs far longer distance than the dimension of the vessel. The electron gains the energy up to 200eV, which is enough to ionize molecules of the residual gas.

<Case 2> B=100Gauss, V=+1kV

The electron has the trace along the magnetic field lines, since the magnetic field is stronger than one in the case 1. Once it moves towards the vessel wall but cannot reach the wall and goes back. It continues repeatedly and the electron gains 60eV in this case all along the long orbit.

<Case 3, 4> B=100Gauss, V=-1kV

The magnetic field strength is same as one in the case 2. They are calculated for two different emission points of an electron. The electron orbits are along the magnetic field line, similar to the Case 2. However they collide the vessel wall soon with the energy of 1keV.

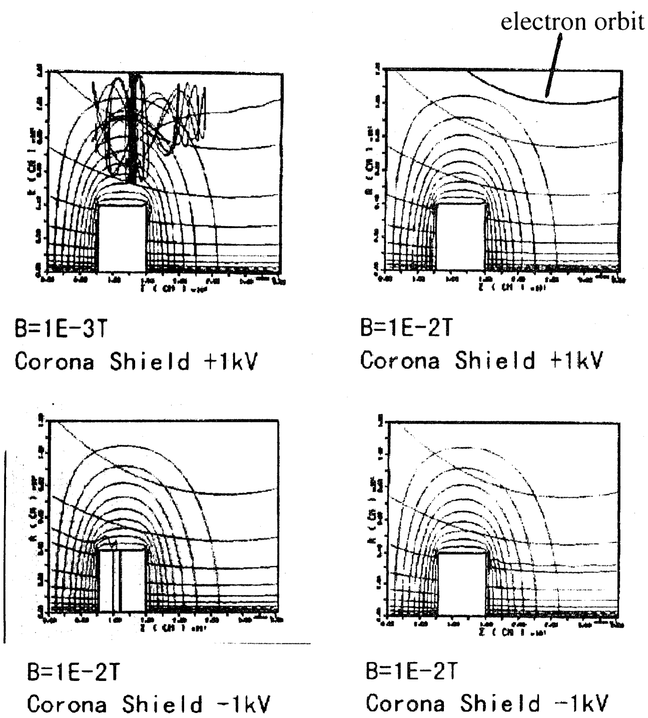

Fig.3 Calculation Results of Electron Orbits in a Magnetic Field by "MIG"

Discussion and Consideration (2)

The calculated results bring the following assumptions.

(1) In case of the positive voltage at the corona shield, the emitted electron from the particular region runs enough long distance and obtains enough energy to ionize molecules of the residual gas. It is thought to cause the discharge.

(2) In case of negative, the emitted electron moves directly to the vessel wall. Thus it doesn't cause the discharge. If the vessel has more complex structure inside, the orbit of the electron may be longer. The further research is necessary.

4. Conclusion and Further Research

The DC discharge limit is reduced under the magnetic field in some cases. It is significant if there is a dip area surrounded with magnetic field lines and metal walls. In such a case the electron strays the dip area and gains the energy. The phenomenon, which is called "Penning trap", is thought to cause the collision between the electrons and the molecules of the residual gas, causing "Penning discharge" even with very small voltage. If electrodes inside grounded vessel have negative voltage, it is often suppressed.

Such a behavior of electrons in a magnetic field has been known in some laboratories in the world, e.g. Joint Institute of Nuclear Research (JINR) [2].

The collision effect of the electron and residual gas molecules is thought to reduce the discharge limit. As it is difficult to simulate the collision effect, more precise analyses have not performed yet. However the numerical approach explain well the tendency of the experimental results qualitatively. Also it gives an important suggestion that such a closed area is not preferable to the gun design.

The higher vacuum level and cleaner surface of the electrodes are thought to keep the discharge limit high.

Further research has been proceeded.

Firstly, experiments were performed to confirm whether the "Penning trap" occurs with electrodes of negative voltage inside the vessel. To note the results shortly, it occurred also with the negative voltage at the corona shield, if the structure of the electrodes were complicated. From the experiences, the authors have revised the supporting method of the T,P,'s to avoid making the dip area.

Following discharge experiments with a ceramic gap or an accelerating tube have begun to be performed. The decrease of the limit in the surface-along discharge has been observed under the magnetic field.

The results have not been analysed in detail. The further discussion and consideration must be necessary, because the discharge limit is quite important to design the real gun configuration for the EC device.

References

[1] H. Danared, Nucl. Instr. And Meth. A335 (1993) 397.
[2] I. Meshkov (JINR), RIKEN-AF-AC-2 (1997)