INTERACTION BETWEEN A COAXIAL CAVITY AND LOW BETA INTENSE ELECTRON BEAMS

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Experiments and simulations for intense relativistic electron beams with energy of <1 MeV and current of several kA that pass through a gap are carried out. A criterion is proposed for the gap length through which the beam current passes without loss, i.e. no electron is reflected by virtual cathode. The time evolutions of energy and current of an intense electron beam can be modified using a gap structure and a coaxial cavity.

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1. INTRODUCTION

Interactions between a coaxial cavity and an intense relativistic electron beam (IREB) with strong self- and induced field are not only interesting for physics but also important for applications. As a typical application of IREBs, intense millimeter electromagnetic wave sources with output power of 1 GW< for nuclear fusion, particle accelerator, etc. utilize IREBs as energy sources. Relativistic klystron amplifiers (RKA), virtual cathode oscillators, and backward-wave oscillators, etc. using IREBs are intensively studied in this decade. Moreover, a new specific mechanism of microwave radiation called superradiance (SR) is proposed [1-3] using an electron beam whose length is shorter than or comparable with interaction length. An IREB with duration of less than 1 ns is requested for millimeter waveband SR. However, it is technically difficult for conventional pulse line system to generate an IREB with pulse duration of less than 10 ns. We proposed multi-stage autoacceleration using a series of passive coaxial cavities with decreasing lengths and obtained an IREB with duration of less than 1 ns from 12 ns IREB [4,5]. The autoacceleration and the RKA use coaxial cavities connected to the drift tube via gaps. The radius of the tube increases suddenly at the entrance of the gap. Propagation characteristics of an IREB through a gap are important subjects to study for autoacceleration, RKA and the devices with a cavity or a gap.

When an electron beam propagates through a drift tube immersed in axial magnetic field, electrostatic potential in the tube due to the beam's space-charge field limits the beam current. In the case of a cylindrical beam propagating through a cylindrical tube, the limiting current is calculated by the initial energy (γ_0) of electrons and the ratio of the beam radius (r_b) to the tube radius (r_t). For an annular beam, the limiting current (I_L) is expressed as below

$$I_L = I_A \frac{(\gamma_0^{2/3} - 1)^{3/2}}{2\ln(r_t / r_b)}, \qquad ($$

where I_A = 17 kA is the Alfven current. The limiting current decreases where the radius of the tube increases. Because of comparatively low energy of IREBs, the space charge limiting current is comparable to the beam current, so that existence of a gap affects strongly to the propagation of the IREB. It is considered that a virtual cathode is formed at the gap and some electrons are reflected when the beam current is much larger than the space charge limiting current at the gap. However, the above equation is derived for the beam with an infinite axial length. In the experiments, it is not clear how long the axial length is enough for a drift tube to apply the above equation. In this paper, we report the length of the gap through which the beam passes without loss and propose the modification of time evolutions of IREB's energy and current using a coaxial cavity and a gap.

2. AN IREB PASSING THROUGH A GAP

We employed a simple model to start this problem. As shown in Fig.1, a drift tube radius increases suddenly from r_1 to r_2 at z (z is the distance from an anode.) and decreases from r_2 to r_1 at $z+d$. The thicker part of the tube with length of d is named a gap here. An electron beam with current I which exceeds the space-charge limiting current I_L at the gap is injected from z=0. We investigate the length d through which the IREB current passes through without loss.

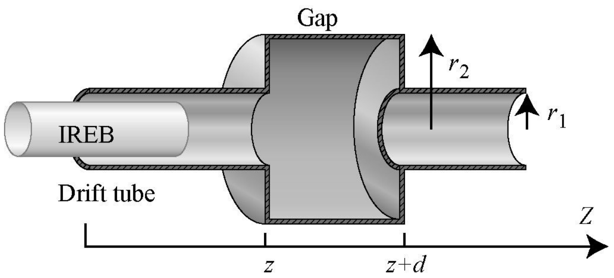

Fig.1 Simple model of a gap

Intense relativistic annular electron beams with energy of ~500 keV, current of 4~8 kA and duration of 12 ns were utilized in the experiment. The beam radius and current were changed. The beam propagated through a drift tube with diameter of 3 cm. A gap with diameter of 12 cm was located 20 cm downstream side of the anode. The length of the gap, d, was changed. The beam current was detected at the end of the drift tube with diameter of 3 cm by a Faraday cup. In order not to affect the presence of the Faraday cup to the experimental results, the Faraday cup was located 20 cm downstream side of the gap end.

Figure 2 shows the beam current waveforms detected at the downstream side of the gap for different gap

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lengths. The space charge limiting current at the gap was evaluated to be 2.8 kA. Though the beam current of 8 kA was much larger than the limiting current, it passes through the gap without loss when the gap length is less than ~30 mm.

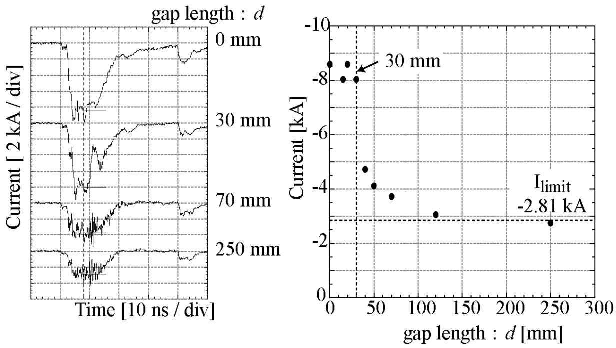

Fig.2. The beam current waveform passing through the gap for different gap lengths (left). The maximum currents passing through a gap are plotted against gap lengths

In Fig.2, the maximum beam currents detected by the Faraday cup are also plotted against the gap length. The beam current decreases to the space charge limiting current at the gap gradually as the gap length increases. The gap length through which the beam passes without loss was also observed experimentally by changing the beam radius and/or current. The gap length through which the beam passes without loss increased as the beam current decreased and it increased as the beam radius increased as expected.

PIC simulation code KARAT was used. As the code KARAT simulated well the experimental results, we extended the range of parameters with energy of 400~1750 keV, current of 3~9 kA and gap radius of 40~90 mm in the simulation. The relation between the gap length and the detected beam current at the downstream side of the gap was investigated with different parameters. As shown in Fig.3, when the gap length is short, the formation of a virtual cathode is incomplete and the injected beam current can pass through the gap without loss. On the contrary, some of the electrons are reflected by virtual cathode, when the gap length is long.

Dependencies of the gap length without loss on the current, energy and radius of the beam indicated the influence of the space-charge limiting current. In Fig.4, the simulated and experimental gap lengths through which the beam current passes without loss are plotted against calculated values of $2(R - r_b)$ for each data, where R is the calculated maximum tube radius for the beam with current I, energy γ_0 and radius r_b by eq.(1). From the simulation results, the gap length increases with $2(R - r_b)$ linearly. And from the experimental results, they also increase with $2(R - r_b)$. We have no physical explanation about this relation yet. The quantitative differnce between the simulated and the experimental results are considered to come from precise differencies of the beam waveform parameters between them.

In conclusion, we propose the gap length of $2(R - r_b)$ as a rough criterion of the gap length through which the beam can pass without loss.

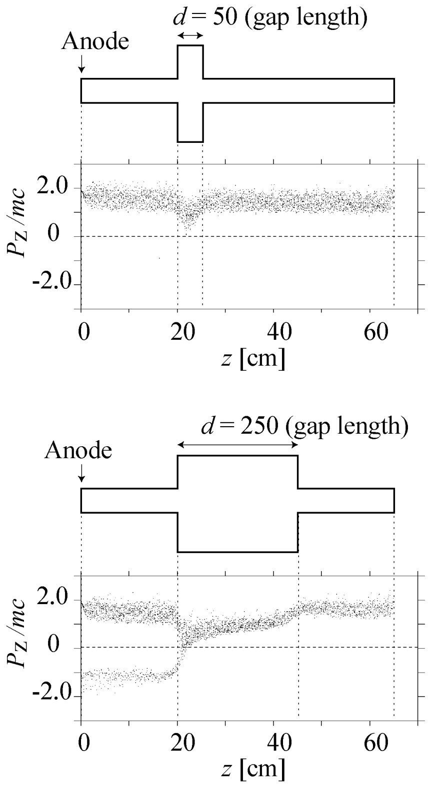

Fig.3. KARAT simulation. Normalized axial momenta of electrons are plotted against the axial position. The formation of virtual cathode is incomplete (up) and the beam current can pass through the gap without loss. Virtual cathode is formed and some electrons are reflected (down)

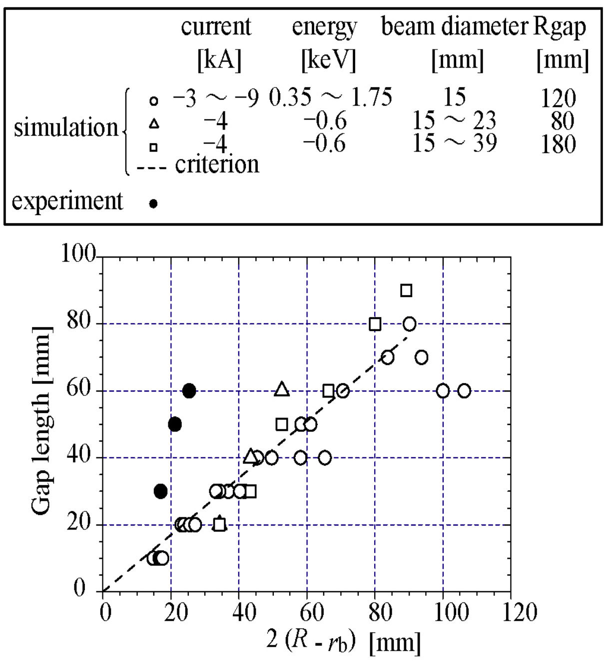

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Fig.4. The gap length through which the beam passed without loss is plotted against 2(R - r_b)

3. ENERGY AND CURRENT INCREASING WAVEFORMS OF AN IREB

For observation of SR, it was proposed in [6] to use an IREB with increasing energy and current in time to increase peak power of SR pulse. As a cold cathode and an anode are utilized for conventional IREB generator, the voltage between diode applied by a Marx generator and a pulse forming line is changed by the evolution of the diode impedance caused by cathode and anode plasmas. There is no way to control the plasmas at the diode. The autoacceleration scheme can be a candidate to realize the IREB with increasing energy in time after the IREB injected from the anode. A coaxial cavity connected to the drift tube via gap is utilized in the autoacceleration. According to the transmission line theory, the gap voltage of a coaxial cavity, $V_g(t)$, is expressed by the current at the gap, $I(t)$, as below[7,8],

$$V_g(t) = Z \times (I(t) - 2I(t-T) + \cdots) \quad (2)$$

where Z is the cavity impedance and T is the round trip time of electromagnetic wave in the cavity. The beam is decelerated for the first period T and accelerated for the next period. As the initial electron energy and current waveforms are not square shape, we have a possibility to obtain a gradual increasing energy IREB using a cavity with appropriate length.

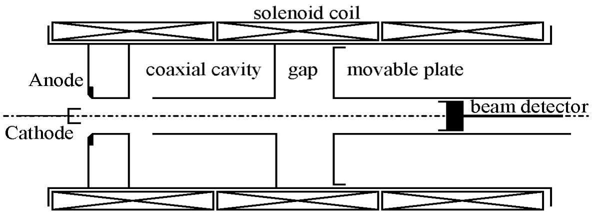

Fig.5. Experimental setup

We used a gap behind the coaxial cavity for autoacceleration in order to decrease the current in low energy part of the IREB. As the enegy of the electrons increases in time after the autoacceleration, we expect that a virtual cathode that reflects only the lower energy electrons is formed with appropriate gap length.

The experimental setup is shown in Fig.5. The parameters of the IREB and experimental apparatus were almost the same as the above experiment. A Faraday cup was used to estimate the kinetic energy of beam electrons. Aluminum foils of various thicknesses were placed in front of the Faraday cup and a transmitted current through aluminum foils was measured. Using the ratio of the transmitted current to the current detected without foil and the range-energy relations, the maximum kinetic energy of beam electrons was estimated.

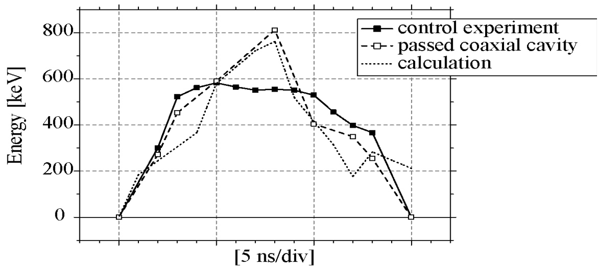

Fig.6. Time evolution of energy with and without coaxial cabity. The cavity length is 60 cm. Calculated results shows good agreement with the experiment

The time evolution of energy detected downstream side of the cavity with length of 60 cm is shown in Fig.6. The time evolution evaluated from the sum of the diode and gap voltages showed good agreements with the experimental results for different cavity lengths. The current waveform was little changed between before and after the coaxial cavity.

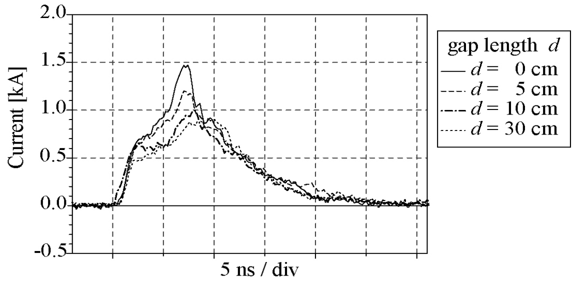

Fig.7. Current waveforms after the gap

The current waveforms after the gap were modified as shown in Fig.7. The time evolution of energy were not changed by the gap. The current at the time with higher energy was more decreased than lower energy part against our expectation. Electrons with lower energy were suspected to be included in the current at the time when higher energy electrons were observed. Precise experiments will be carried out for this problem.

In conclusion, the time evolutions of electron energy and current can be changed using a coaxial cavity and a gap within the limit of initial diode waveforms. In connection with the design of a new diode, time evolutions of energy and current become easier to modify.

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REFERENCES

1. N.S. Ginzburg, I.V. Zotova // *Sov. Tech Phys. Lett.* 1989, v. 15, p. 573-574,
2. N.S. Ginzburg, I.V. Zotova, A.S. Sergeev, I.V. Konoplev, A.D.R. Phelps, A.W. Cross, S.J. Cooke, V.G. Shpak, M.I. Yalandin, S.A. Shunailov and M.R. Ulmaskulov // *Phys. Rev. Lett*. 1997, v.78, p.2365-2368,
3. S.M. Wiggins, D.A. Jaroszynsky, B.W.J. McNeil, G.R.M. Robb, P. Alitken, A.D.R. Phelps, A.W. Cross, K. Ronald, N.S. Ginzburg, V.G. Shpak, M.I. Yalandin, S.A. Shunailov and M.R. Ulmaskulov // *Phys. Rev. Lett*. 2000, v. 84, p.2393-2396.

4. D. Hasegawa, K. Kamada, K. Shimizu, R. Ando and M. Masuzaki // *IEEE trans. Plasma Sci*. 2000, v.28, p.1648-1652.
5. D. Hasegawa, K. Kamada, A. Kuraku, R. Ando and M. Masuzaki // *Jpn. J. Appl. Phys*. 2001, v. 40, p.944-948.
6. N.S. Ginzburg, I.V. Zotova, R.M. Rozental, A.S. Sergeev, M. Kamada, K. Sugawara, K. Kurihara, H. Shirasaka, R. Ando, K. Kamada // *Proc. 14th Int. Conf. High-Power Particles Beams*. 2002, p.291-294.
7. M. Friedman // *Appl. Phys. Lett*. 1982, v. 41, p.419-421,
8. M. Kamada, R. Ando, N.S. Ginzburg and K. Kamada //*IEEE trans. Plasma Sci*. 2003, v. 31, p.297-299.

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ВЗАИМОДЕЙСТВИЕ МЕЖДУ КОАКСИАЛЬНЫМ РЕЗОНАТОРОМ И ИНТЕНСИВНЫМИ ЭЛЕКТРОННЫМИ ПУЧКАМИ С МАЛЫМИ БЕТА

Кеичи Камада, Такаши Нишигучи, Кеичи Ишибана, Масаки Камада, Ритоку Андо

Представлены экспериментальные исследования и численное моделирование процессов автоускорения при прохождении интенсивных релятивистских электронных пучков (энергия порядка 1 МэВ и ток несколько килоампер) через коаксиальные резонаторы. Найден критерий на длину зазора между резонаторами для образования виртуального катода.

ВЗАЄМОДІЯ МІЖ КОАКСІАЛЬНИМ РЕЗОНАТОРОМ І ІНТЕНСИВНИМИ ЕЛЕКТРОННИМИ ПУЧКАМИ З МАЛИМИ БЕТА

Кеичи Камада, Такаши Нишигучи, Кеичи Ишибана, Масаки Камада, Ритоку Андо

Представлено експериментальні дослідження і чисельне моделювання процесів автоприскорення при проходженні інтенсивних релятивістських електронних пучків (енергія порядку 1 МеВ і струм декілька килоампер) через коаксіальні резонатори. Знайдено критерій на довжину зазору між резонаторами для утворення віртуального катоду.