# DEVELOPMENT OF A HIGH CURRENT INJECTOR WITH THERMIONIC CATHODE ELECTRON GUN FOR A SUPERCONDUCTING RF LINAC*

A. B. Kavar†, F. Hinode, I. Nagasawa, K. Nanbu, K. Kanomata, K. Shibata, K. Takahashi,
K. Kumagai, K. Kudo, S. Kashiwagi, T. Muto, H. Hama , Tohoku University, Sendai, Japan
K. Masuda, National Institutes for Quantum and Radiological Sci. and Tech. (QST), Aomori, Japan

## *Abstract*

We are conducting research on a thermionic gridded electron gun with high average current for a superconducting electron linac which will be used for wastewater purification. The electron gun will generate the pulsed beam by using a DC high voltage and driving the grid at high speed. The current dependence of emittance is investigated numerically based on the existing electron gun setup. We will now proceed to optimize and improve the geometry and configuration of the injector components such as focusing magnets and bunching cavities to inject a high current beam into the superconducting RF cavities. In order to evaluate the actual beam produced by the electron gun, a test stand for the electron gun is currently being constructed. In this paper, we will discuss the results of numerical studies and the current status of the electron gun test stand.

## INTRODUCTION

The growing global concern about water pollution and shortage in recent years has highlighted the need for effective wastewater treatment solutions. Among the emerging technologies, Electron Beam (EB) accelerator-based wastewater treatment has received a lot of interest because of its potential to provide a robust and sustainable solution [1]. Studies have demonstrated an extraordinary cleaning ability of EB based treatments [2, 3]. However, such treatments can be commercially successful only if they are economically viable. To establish an economically viable EB-based plant, several key requirements such as high beam current for effective treatment rate, scalability to handle varying wastewater flow rates, compact design making it suitable for integration into existing facility, low maintainence requirement etc. need to be met. Linear accelerators based on conduction cooled, Superconducting Radio Frequency (SRF) technology have been an ideal choice in regards to the necessity of meeting these requirements. We are therefore focusing our efforts on using SRF technology for wastewater treatment.

Our overall aim is to design and develop a compact, high-current electron linear accelerator using a $Nb_3Sn$ SRF cavities with a conduction cooling system. The $Nb_3Sn$ SRF cavities in the main accelerator section is being developed in collaboration with KEK and NIMS. The injector part including an electron gun and buncher section will be designed and experimentally tested at ELPH, Tohoku University. For stable operation of the SRF accelerator, the electron injector system should provide an accurately shaped short bunches without tails and halo [4]. Because even a small amount of beam loss in the superconducting cavity will cause a quench. Most common approach to fulfil this requirement is an rf photoinjector which can generate picosecond electron bunches but requirement of drive laser makes the geometry complex, costly and maintenance extensive. On the other hand, thermionic emission is a less complex method which is able to provide high current density with additional benefits of structure simplicity, high emission capability, low maintenance, low cost and also, the ease in finding the spares. However, to produce short electron bunches, the cathode grid must be controlled at high speed. We have initiated study for the development of an injector comprising a DC thermionic gridded electron gun operated by a fast grid pulser followed by a bunching section with conceptual schematic as shown in Fig. 1. In this paper we will discuss about the prototype of accelerator system, the targeted design parameters and the numerical studies of electron source.

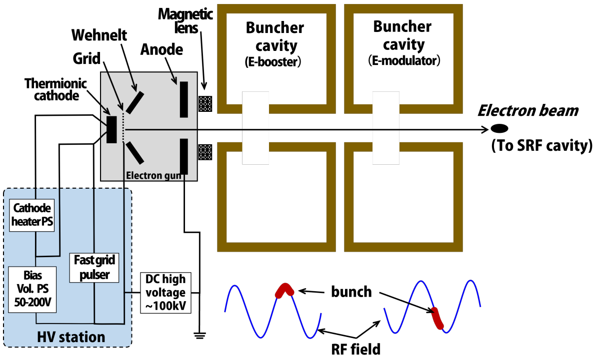

Figure 1: Schematic of proposed high-intensity injector.

## EB BASED WATER PURIFICATION

When water is subjected to EB, it produces highly reactive species [5] such as OH·, H·, $e^-$ and other secondary reactive species within 1 µs as shown in Fig. 2. These short-lived radicals carry out a cascade of simultaneous oxidation and reduction reactions breaking down organic and inorganic pollutants into simpler compounds. As a result 70-100 % of degradation, removal, and detoxification of pollutants present in water has been observed [1]. Furthermore, the radicals disrupt the cell membranes and genetic material of microorganisms, leading to their inactivation with an effective dose of 1-2 kGy [6].

No additional chemicals are required to start these reactions. Most notably, both highly oxidizing and reducing

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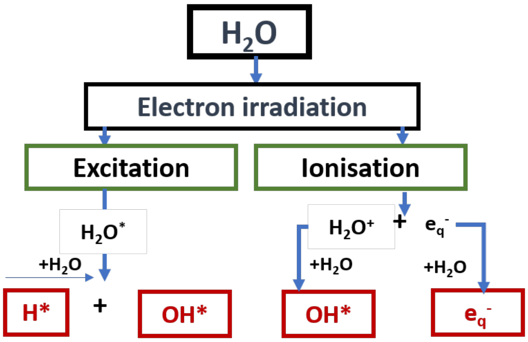
† kavar.anjali.bhagwan.r4@dc.tohoku.ac.jp



| Product | $e_{aq}^-$ | $H^*$ | $H_2$ | $H_3O^*$ | $H_2O_2$ | $OH^*$ | $OH^-$ |
|---|---|---|---|---|---|---|---|
| G(μmol/J) | 0.28 | 0.06 | 0.04 | 0.033 | 0.07 | 0.28 | 0.05 |
| Nature | Reducing | | | | Oxidizing | | |

Figure 2: Various reactive ions and radicals produced by electron beam irradiation of water.

reactive species are generated simultaneously with an yield higher than any other advanced oxidation process. EB-based processing also offers an additional benefit of Process controllability and Compatibility with conventional methods.

## DESIGN PARAMETERS AND CHALLENGES

High-power accelerators are being designed and developed to build economically viable EB-based plants. We set our first target such that the accelerator system will be capable of processing 5 million liters per day (MLD) of water at a dose of 2 kGy. Assuming an irradiation efficiency of 60%, the required beam power is 200 kW from Eq. (1).

$$\text{Power(kW)} = \frac{\text{Dose(kGy)} \times \text{Water amount(kg/s)}}{\text{efficiency}} \quad (1)$$

The transfer efficiency of power from an electron beam to water strongly depends on the irradiation system, such as electron beam energy and scanning beam size at the irradiation point, and so on. The efficiency of 60 % is set with reference to the EB treatment plant using 1 MeV DC accelerator in South Korea [7] and the proposed treatment plant using 10 MeV SRF accelerator by Fermi Laboratory [8]. In our design, five L-band single cell SRF cavities are used to accelerate the beam up to 5 MeV. Average beam current is 40 mA with 200kW of beam power. Each cavity cell is equipped with a coupler of 40 kW to feed the RF power for the accelerating gradient of about 10 MV/m.

The SRF linac injector to be developed with an average beam current of 40 mA includes a DC-grid thermal electron gun and a sub-harmonic buncher system operating at 216 MHz, which corresponds to 1/6 of the linac's RF frequency of 1.3 GHz. To achieve an average current of 40 mA, the repeition rate required must be feasible. Presently, the available pulser, developed by Kentech Instruments Ltd., can achieve a maximum repetition rate of 27 MHz with 400 ps in FWHM. Considering the space charge limit, if cathode is operated for a Gaussian electron bunch with a charge of 1 nC and a bunch length of $\sigma_t$ = 167 ps ($6\sigma_t$ = 1ns), a bunch repetition rate of 40 MHz will be necessary. Our challenge is thus to develop a high-speed grid pulser that can operate at 40 MHz or higher. We will develop a fast grid pulser using two transistors and step recovery diode that operate at high speed. Another and most important aspect is the emittance of the electron beam produced by the electron gun which must be small enough to avoid beam loss in the superconducting cavities.

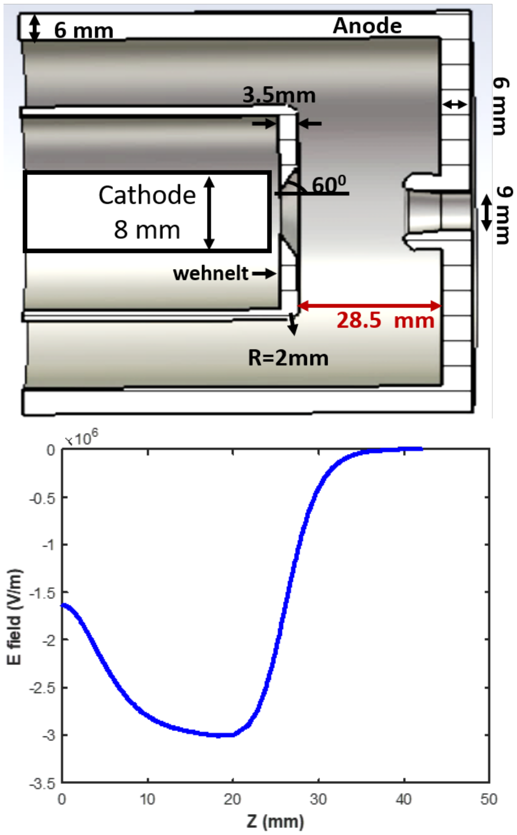


Figure 3: Geometry of the electron gun (Up). Vacuum field distribution along beam axis in the gun (Down).

Adhering to these goals, our initial focus will be to build an electron gun test stand at the ELPH facility and develop the high repetition rate, high average current electron gun. We will then investigate the current dependence of emittance and bunch length.

## NUMERICAL STUDIES OF GUN

Numerical study has been performed for an existing gun [9]. Geometry of the gun and the electric field distribution of the gun is as shown in Fig. 3. At a first, we wanted to investigate current dependence of electron beam emittance using simulation code of CST [10]. To start with, this study was performed with CW beam for the current range of 100 mA to the maximum achievable current of 2.5A with gun voltage of 72 kV. The results were demonstrating an

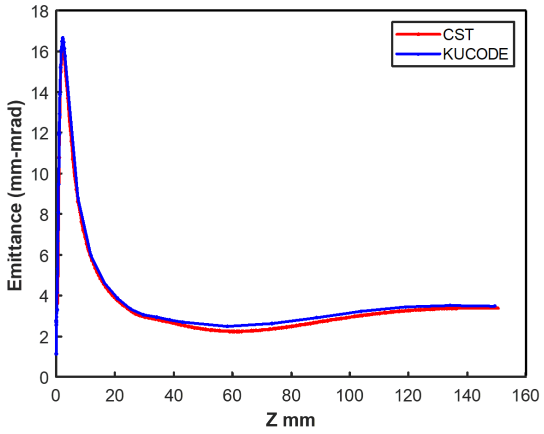


Figure 4: Emittance evolution along the beam axis calculated with CST and KUCODE for 1A with 72 kV of gun potential.

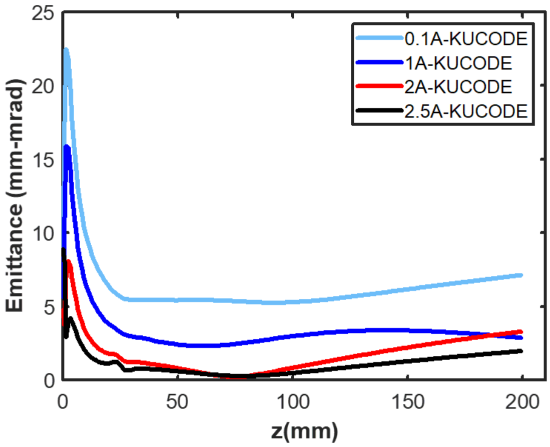


Figure 5: Variation of the beam emittance along longitudinal direction for different beam current.

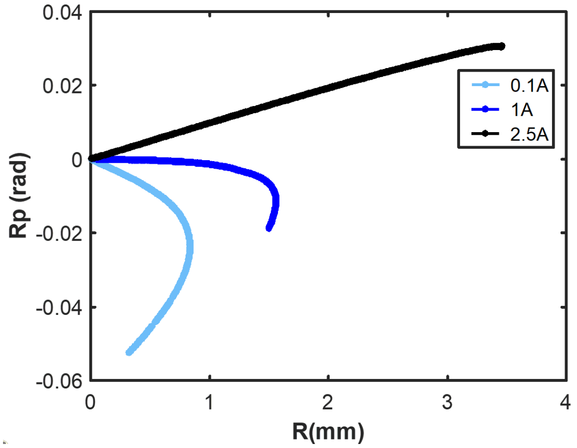


Figure 6: Phase space distribution for 0.1A, 1A and 2.5A at 5 mm downstream the anode i.e. at 42 mm from cathode surface (z=0).

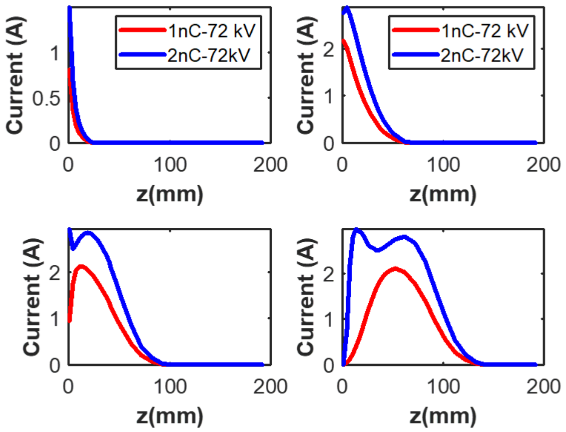


Figure 7: Beam extraction from thermionic cathode with 72 kV for different bunch charge.

uncommon trend of almost the same emittance value for different currents. We therefore used KUCODE [11], which has been used for electron gun simulations, and compared our results with those of CST. The current dependence of the emittance calculated by the two codes was different. Focusing on the difference in the phase-space distribution of the beam emitted from the cathode, a modification was made to reduce the mesh size of the cathode surface. By modifying mesh cells and mesh size for the gun geometry within CST, we obtained very close results with CST and KUCODE as shown in Fig. 4. From this modification, it was found that emittance is sensitive to the mesh around the cathode surface and that the mesh should be set carefully. The emittance obtained after the mesh optimization was not constant and decreased with increasing beam current as shown in Fig. 5. Analysis of transverse fields (space charge and vacuum field) acting on beam stated the reason of an inter-play between beam spreading space charge force and the focusing vacuum field. Space charge effect is low for lower current resulting in a stronger transverse focusing due to vacuum field. As a result, phase space distribution of the beam for higher current becomes linear whereas there comes non-linearity in the beam for lower current as shown in Fig. 6, giving an above result of decreasing emittance with current.

Simulations for bunched beam are then performed with optimized mesh cells and mesh size in CST. First of all, we wanted to investigate the pulse lengthening due to bunch charge and gun voltage. In this study, simulations involving gun potentials of 50 kV, 72 kV and 100 kV and bunch charge of 1nC and 2nC have been performed. An initial bunch length of $\sigma_t = 167$ ps ($6\sigma_t = 1$ns) was assumed. With a bunch charge of 1 nC, the peak current corresponds to about 2 A. While studying the effect of bunch charge on pulse lengthening, two peaks has been observed for higher bunch charge, whereas no such peaks were observed for lower bunch charge as shown in Fig. 7. These peaks represent suppression of charge extraction due to the influence of space charge. From the simulations, the space charge limits for potentials of 50 kV, 72 kV, and 100 kV are obtained to be

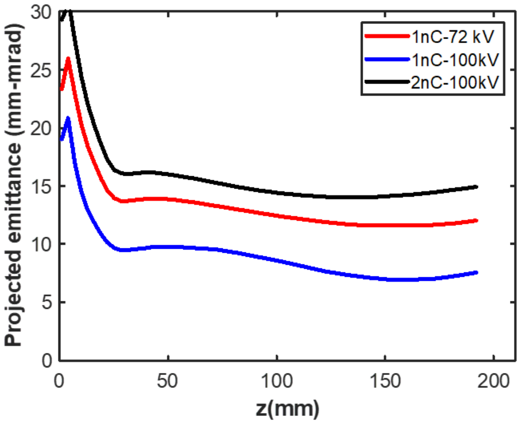


Figure 8: Emittance variation of a 1 nC and 2 nC bunch for different gun potential.

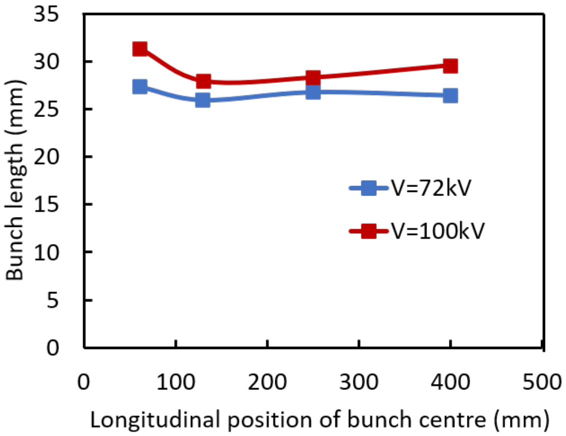


Figure 9: Bunch length variation along longitudinal position with different potential (72 kV and 100 kV). Bunch charge is 1 nC.

approximately 0.6 nC, 1.7 nC, and 2.6 nC, respectively. To get a desired average current of 40 mA with a feasible repetition rate, bunch charge of at least 1 nC needed to consider. The further study we therefore have performed for the gun potential of 72 and 100 kV. With the same bunch charge of 1 nC, emittance for higher gun potential is less as compared to that of lower gun potential as shown in Fig. 8. Also, no significant difference in bunch length for 72 and 100 kV as shown in Fig. 9. Emittance for higher bunch charge of 2nC for 100 kV has also been checked for which the emittnace is even larger than that for 1 nC, 72 kV. Further optimizations including solenoid and buncher system will therefore be performed with bunch charge of 1nC and 100 kV.

## EMITTANCE MEASUREMENT METHODS

Actual evaluation of the beam becomes necessary to validate, refine, and provide a ground truth that simulations can be compared against. We therefore want to evaluate the beam experimentally.

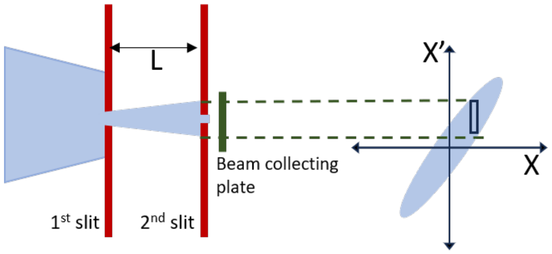


Figure 10: Principle of double slit emittance measurement.

There exist various techniques for the experimental quantification of the emittance. Methods used for high energy electron beam uses interactions of the beam with probes used for measurement. However, no such directional interactions can be observed at low energy. Alongwith this, space-charge effects which are much prominent at low enegies leads to the beam spreading affecting the accuracy of emittance measurements. However, there are few methods that are most commonly used for effective measurement of the emittance without getting influenced by space charge. These are slit-and-grid systems and pepper-pot techniques.

Pepper pot is a most commonly used as it gives a single shot measurement. In this method, a beam is stopped by a mask containing holes. Only a small part of the beam i.e. beamlets are allowed to pass through these holes. Since the charge is significantly suppressed, the beamlets are emittance dominated and thus they traverse the drift with beam divergence only. After a proper drift, a scintillator screen produces an image of the beamlets. Analysis of the size evolved and the intensity passed through the holes gives the emittance value. However, a whole beam can not be scanned with this method as for the precise measurement of the beam divergence, two beamlets should not overlap on the screen constraining the holes to be placed apart [12]. To perform pepper pot emittance measurement as per the beam properties, we therefore need to fix hole dimension, drift length and hole separation which are interdependent.

Comparatively, the principle of double slit emittance method in which two slits are used to measure emittance as shown in Fig. 10, allows the whole beam scan. In this methode, first slit of the device restricts the width of the particle beam in one direction creating a narrow, emittance dominated beamlet. After traversing the drift length L from first slit, the profile of the small beamlet is measured by the second slit. For every position of first slit, there is corresponding profile scan of second slit. By scanning both slits throughout the whole beam area, a beam distribution in the transverse phase space obtained at the second slit position can be retraced back to get phase space data at first slit position and hence the emittance.

Therefore to perform the double slit scan, parameters such as slit width and drift length L need to be fixed. These parameters does not have any interdependence. We therefore can find the suitable values for these parameters. In order to evaluate the actual beam produced by the electron gun, we therefore have decided to use double slit emittance measure-

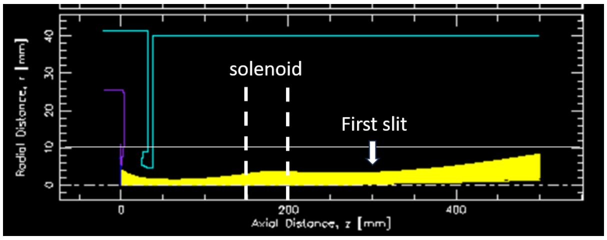


Figure 11: Electron beam trajectory after focusing.

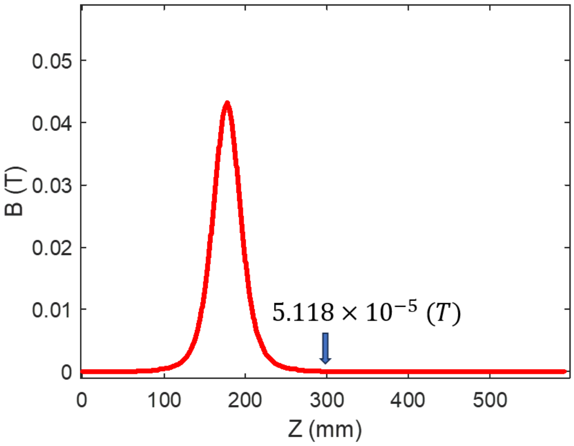


Figure 12: Solenoid field strength at first slit location.

ment method. The double-slit apparatus at the ELPH facility can accommodate a beam with a diameter of 30 mm. In response to this, we have employed a solenoid with which the beam size is effectively reduced to a value significantly less than 10 mm, as depicted in Fig. 11. The initial position of the first slit has been strategically chosen to be 300 mm away from the cathode's surface, as this is a region characterized by a relatively weak magnetic field strength, as illustrated in Fig. 12. The precise arrangement and configuration of the double-slit setup including slit width and dirft length L will now be determined through an analysis of the simulation by the CST software.

## SUMMARY

In the pursuit of an economically viable wastewater treatment solution, our research focuses on developing a high-current thermionic injector for a superconducting electron linac. The system incorporates a DC gridded thermionic electron gun and a sub-harmonic buncher system which will generated an average current of 40 mA. Numerical studies performed till now have showed that there is no bunch lengthening over the drift of 400 mm for the bunch with 1 nC bunch charge and $\sigma_z$ of 0.167 nS. Further studies concluded that for bunch charges of 1 nC to 2 nC, a gun voltage of 100 kV is more suitable than 72 kV in terms of beam emittance. Additionally, to accurately evaluate the emittance of the produced electron beam, we are planing to implement a double-slit emittance measurement method.

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