4K SUPERCONDUCTING RF ELECTRON GUN

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Abstract

A superconducting accelerator is an excellent technology that can efficiently accelerate high-current beams and is being applied to free electron lasers and next-generation linear electron-positron colliders such as ILC. Not only for the fundamental science, but also the high current electron beam plays a rather important role in industrial and medical applications. This is because the demand for high-current beams is also strong in these applications. While superconducting accelerators are becoming more widely used, there are not many examples in practical use of the superconducting RF gun, such as the ELBE RF Gun in HZDR. The entire accelerator should be superconducting for its energy efficiency and technical compatibility. To bridge this technical gap, we propose a superconducting RF gun utilizing the latest 4K superconducting technology, which can generate continuous, high-brightness beams. As the cathode, we study both the photo and thermionic cathodes.

INTRODUCTION

Recent technological demands have intensified interest in CW Relativistic Electron Beam (CWREB). Their unique properties make them indispensable in diverse applications such as CW free-electron lasers (CW FELs), sterilization of medical, medicine, and food packaging, RI production, and inspection of large-scale infrastructure etc. As a result of the development of the superconducting accelerator technology especially by TESLA project followed by ILC project, this technology has been well matured and the superconducting accelerator is now widely used in many advanced accelerator project, XFEL [1], ELBE [2], LCLS-II [3], SHINE [4], and expected to be used in ILC [5]. However, the electron source for these projects are DC biased electron guns or Normal conducting RF gun. One of the exception is ELBE in HZDR which employs SRF Gun operated at 13 MHz CW up to 1-mA beam current [[6, 7]]. This is only one demonstrated example for CWREB.

On the other hand, there are strong demands for the CWREB source from not only the scientific facilities like FELs and colliders, but also from industrial and medial applications. Sterilization technology has become an important infrastructure for modern medicine. One of the biggest issue is the high price of existing electron beam sterilizers. Currently widely used sterilization methods are displayed on a cost (horizontal axis) and safety and risk (vertical axis) plane in Fig. 1.

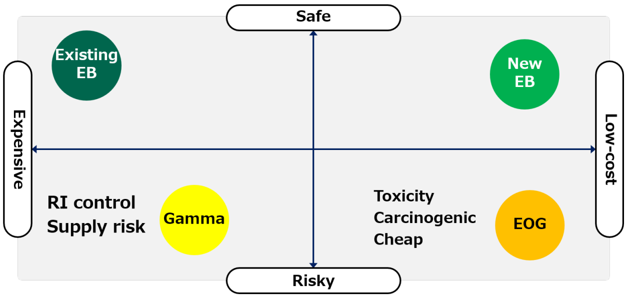

Figure 1: Currently widely used sterilisation methods are displayed on a cost (horizontal axis) and safety and risk (vertical axis) plane.

While electron beam sterilization (EB) is safe, risk-free and stable in its supply, its cost is very high compared to other methods. EOG (Ethylene Oxide Gas) sterilization is inexpensive and there is no concern about supply, but health hazards due to gas residues have been raised and it is also known to be carcinogenic. Public health authorities such as the Japanese Ministry of Health, Labour and Welfare and the US FDA have stated that EOG sterilization is an undesirable method and is only allowed to be used when no other suitable alternative method applicable.

Gamma sterilization requires large quantities of radioactive isotopes that emit gamma rays, such as Co, but the nuclear reactors used for RI production are aging and there are global supply concerns. CWREB SRF Gun is a good candidate to solve these issues. EB sterilization needs typically ~5-MeV electron beam. CWREB SRF Gun can generate the required beam of energy on its own, enabling compact and inexpensive electron beam sterilizers.

Targeted alpha therapy (TAT) using Actinium-225 (^{225}Ac) is an emerging and highly promising approach for treating certain types of cancer [8]. It combines the high-energy, short-range cytotoxicity of alpha particles with the specificity of molecular targeting, enabling selective destruction of tumor cells while sparing surrounding healthy tissue. ^{225}Ac is a radioactive isotope that emits alpha particles during its decay chain which is suitable for TAT. High purity is required when producing isotopes for use in radio pharmaceuticals.

Figure 2 shows cross-section of the photo nuclear reaction of $^{226}\mathrm{Ra}(\gamma, n)^{225}\mathrm{Ra}$ peaked at 10–15 MeV [9]. For the RI production, CWREB is useful in energy of 30 MeV or more to generate gamma in the energy region by Bremsstrahlung. The production of radioisotopes via photonic nuclear reactions offers several advantages. The high penetrating power

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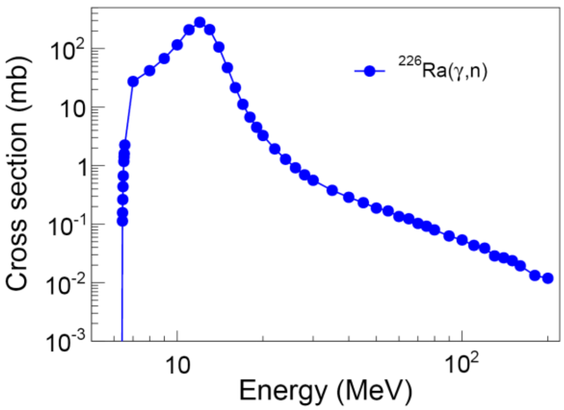

Figure 2: Cross section of $^{226}Ra(\gamma,n)^{225}Ra$ as a function of photon energy.

of gamma rays allows for the use of large production targets, making this method suitable for the large-scale production of RI. Furthermore, because photonic nuclear reactions generally have limited production channels for RI, they enable the production of higher-purity radioisotopes.

Additionally—and this is a characteristic specific to the production of ^{225}Ac via gamma rays—the product contains virtually no impurities. Both ^{225}Ra and ^{225}Fr ultimately decays into ^{225}Ac. Furthermore, since ^{224}Fr and ^{224}Ra pass through Rn during their decay processes, they become gaseous and escape at that stage. This contrasts with the production of ^{225}Ac via proton beams, where ^{224}Ac is produced in addition to ^{225}Ac.

CWREB is also useful for material processing. With CWREB, high-throughput and non-contact methods for surface treatment and modification of various materials is possible. It is also applicable for non-destructive inspection with X-rays, muons, or neutrons which can be generated as the secondary particle of CWREB [10].

4K SRF GUN

The biggest concern in CW operation of superconducting RF electron guns is cryogenic power. Currently popular superconducting acceleration techniques use Nb as the structural material of the cavity, with an operating temperature of 2 K. The Carnot efficiency is determined as the ratio of the low temperature bath and the high temperature bath giving 0.7%, whereas the actual efficiency of cryogenics is approximately 0.2%.

To address cryogenic power challenges in CW operation, $\mathrm{Nb_3Sn}$-coated SRF cavities are being investigated, because higher operating temperatures (up to 4.4 K), reduced surface resistance and cryogenic load, achievable gradients exceeding 20 MV/m as an estimate based on demonstrated experimental values [11].

$\mathrm{Nb_3Sn}$ has a critical temperature of 18 K, which is twice higher than that of Nb. Nb_3Sn is highly brittle and difficult to fabricate in the same way as Nb cavities; however, a method of plating or depositing Sn on Nb cavities and then heating to promote the reaction to form a Nb_3Sn film on bulk Nb has been tested. 24 MV/m (Single cell, 4.4 K) and 10 MV/m (9 cell, 4.4 K) fields have already been demonstrated [11].

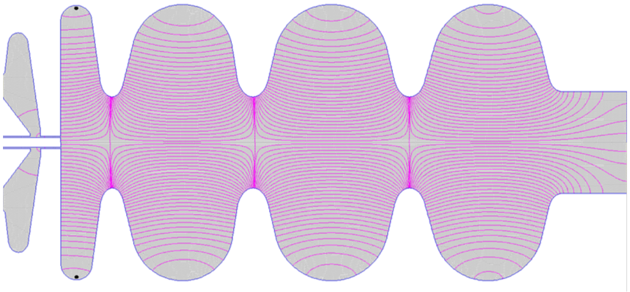

Figure 3: Cross-sectional view of the 3.5 cell SRF Gun in 2.6 GHz frequency.

Based on the technology of 4K $\mathrm{Nb_3Sn}$ coated superconductor, a 3.5-cell SRF gun operating at 2.6 GHz was designed. The design concept of the gun cavity is same as that for ELBE SRF Gun [6] except the frequency. Figure 3 shows the cross-sectional view of the cavity with the RF mode simulated with SuperFish [12].

The shunt impedance of the cavity was $R = 8.4 \times 10^{12}\Omega/m$ and Q-value was $Q_0 = 2.8 \times 10^9$. With 20 W input, the cavity gradient becomes 20.7 MV/m and the beam energy at the exit of the gun is 4.1 MeV. The Lorentz gamma factor exceeds 8 and the beam is already relativistic.

The cryogenic efficiency is 0.4% which is double of 2K operation. Not only is the cooling efficiency high, but the difference in operating temperature between 2K and 4.4K is large. Since the boiling point of liquid helium is 4.2K, cooling down to 2K requires depressurization to lower the boiling point. For this purpose, the cryogenics needs additional facilities such as pumps for depressurization, large bags for storing large amounts of evaporated gas helium, and cold box for storing liquid helium under depressurized conditions and cooling it down to 2K.

Operation at 4.4 K eliminates the need for these facilities, greatly simplifying the system and reducing costs. In 2K operation, because the cryomodule must be depressurized, the entire vessel must be designed to withstand pressure. Consequently, in addition to the technical requirement to strengthen the structure, administrative constraints—such as safety inspections—and the associated workload increase dramatically. In 4.2K operation, in addition to being technically simpler, administrative constraints and the associated workload are significantly reduced.

PHOTOCATHODE OPTION

Photocathode compatibility with SRF environments is essential. Candidates include:

- Heat processed Mg cathode: Clean operation (no contamination), but limited QE. To generate a large beam current, a high power UV laser (266 nm) is required.
- $\mathrm{Cs_2Te}$ cathode: High QE for UV light (266nm) and a potential for high current operation, but more sensitive to SRF vacuum conditions because it is generated as a

Table 1: Laser Power to Generate Required Beam Current

Cathode material	**QE**	**Wave Length (nm)**	**0.1 mA (W)**	**1mA (W)**	**10mA (W)**
LC Mg	2e-3	266	0.24	2.4	24
Cs_2Te	1e-2	266	0.047	0.47	4.7
CsK_2Sb	5e-2	532	0.0047	0.047	0.47

thin film by evaporation on a substrate. Contamination by exfoliation or desorption is possible. On the other hand, this cathode is used daily in ELBE SRF Gun [6] and the compatibility to SRF cavity is confirmed [13].

- CsK_2Sb cathode: High QE [14] with green light (532 nm) excitation and robustness is high [15]. Studies suggest the possibility of 10 mA operation if cavity contamination can be avoided, but the operation of this cathode in a SRF Gun is never confirmed.

The performance and required laser power of the cathode material is summarized in Table 1. Nb_3Sn accelerator cavity technology has already been studied and the performance required for this proposal has already been demonstrated in a single cell test cavity, so the issue is reproducing the equivalent performance in the gun cavity. In addition, all cathodes are basically established technologies, and the cathodes themselves do not require much development.

On the other hand, there are many potential technical challenges in integrating the cathode and cavity: Mg and Cs_2Te cathodes have been proven in the ELBE SRF Gun, but CsK_2Sb cathodes have not. Operation at high currents requires increasing the power of the laser, that means that almost all of the laser power scattered by the cathode is absorbed in the cavity, increasing the heat load and making it difficult to operate the superconducting cavity. Therefore, the use of cathodes with high quantum efficiency is necessary for high-current operation. If the heat load of 1 W is used as a guideline, the possible current with a Mg cathode is about 0.1 mA, with a Cs_2Te cathode 1 mA, and with a CsK_2Sb cathode 10 mA.

THERMIONIC CATHODE OPTION

Thermionic cathodes have an advantage generating higher average current than the photo-cathode can generate. However, the emission from the thermionic cathode is basically continuous and difficult to control in RF acceleration. SRF cavities are very sensitive to the beam loss, which causes performance degradation and possible quench. RF gating (high-frequency grid control) of a thermionic cathode is a fundamental technique used to produce electron bunches synchronized with the accelerating RF field [16]. Thermionic RF gating remains a robust and high-duty-cycle solution.

RF gating for a thermionic cathode works by superimposing a high-frequency RF signal onto a negative DC bias applied to a control grid. The constant DC bias normally keeps the gun in a ”cut-off” state, preventing electron emission. When the RF voltage peaks, it momentarily overcomes this bias, allowing a short bunch of electrons to escape during a fraction of the RF cycle. This technique enables the generation of sub-nanosecond pulses that are inherently synchronized with the phase of the subsequent acceleration cavities. Consequently, it provides a stable and high-repetition-rate electron source for advanced particle accelerators.

The duration of an electron pulse generated via thermionic emission with the RF gating with S-band, the shortest pulses produced directly at the grid are approximately 150 ps in full width. This duration is primarily dictated by the technical constraints of electron transit time between the cathode and the grid, as well as the achievable steepness of the RF voltage rise. Further reduction is possible placing this 150 ps pulse around zero cross of the main RF (RF field in SRF gun cavity).

Let us assume the emission from thermionic cathode is controlled by the RF gating from $t = 0$ to $t = 150$ ps. If the main RF field is given as $E = \sin[\omega(t - t_0)]$ with $0 < t_0 < 150$ ps, the emission is limited between $t = t_0$ and 150 ps, because the electrons emitted from the cathode go back to the cathode by the deceleration field of the main RF. The emission is controlled not only by the RF signal applied to the grid, but also the main RF. By employing this technique, we can controlled the emission from thermionic cathode to prevent the beam loss in SRF cavity.

SUMMARY AND CONCLUSION

CWREBs are essential for the advancement of many modern technologies. With the integration of Nb_3Sn SRF cavities operated at 4K and advanced photocathodes, the development of compact and efficient CW electron sources is becoming feasible. Future efforts will focus on high-QE, SRF-compatible cathodes and system integration for practical applications. Heat control for the input coupler and manage HOM from the beam instability and the heat load points of view are essential for the high current operation.

The project is being advanced in collaboration among Hiroshima University, NovAccel Co. Ltd., HZDR, and FRIB. Currently, the collaboration aims to obtain competitive funding not only for fundamental science and technology, but also for commercialization funding for industrial and medical applications including a matching fund between academic organizations and a private company. The collaboration is rather suitable for the matching fund. With the funds obtained, we plan to conduct basic tests on the compatibility of the cathode and superconducting cavity, evaluate heat generation from the coupler, evaluate heat generation from the HOM, create a prototype, confirm RF and heat load characteristics, and then proceed to beam generation tests. Under the current plan, testing of the first prototype is scheduled to begin at Hiroshima University by the end of 2026.

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