A PROPOSAL OF SUPERCONDUCTING RF ELECTRON GUN WITH THE LATEST 4K SUPERCONDUCTING TECHNOLOGY FOR CW HIGH BRIGHTNESS ELECTRON BEAM GENERATION

M. Kuriki*, L. Guo, Z. Liptak, U. Hiroshima, Higashihiroshima, Japan
H. Hayano, NovAccel Co. Ltd., Tsuchiura, Japan
A. Arnold, J. Teichert, and R. Xiang, Helmholz-Zentrum Dresden-Rossendorf, Germany
T. Konomi, FRIB, East Lansing, US

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.

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 in 13 MHz CW up to 1mA 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. Sterilization of metal surgical instruments, for example, by heating (autoclave), spread relatively quickly. On the other hand, heat sterilization cannot be used for disposable syringes and non-heat-resistant medical instruments such as bags and tubes for intravenous infusions and transfusions, and there have been incidents of viral hepatitis spread when the same syringe is used for vaccinations to many people. The widespread use of sterilization will prevent such incidents, but even today there are still issues. One of them 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. While electron beam (EB) sterilizationis 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 and gas leak to environment have been raised and it is also known to be carcinogenic.In the United States, cancer is prevalent among residents living near sterilization plants, which has become a social issue. In response to complaints from residents, the courts have recognized the causal relationship, and sterilization companies are now burdened with paying large amounts of compensation to residents. 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 (Co60) that emit gamma rays, 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. Particular attention must be paid to isotopes of the same element with different mass numbers, as they are difficult to separate. Transmutation through photo-nuclear reaction using an electron beam is a method suitable for

* mkuriki@hiroshima-u.ac.jp

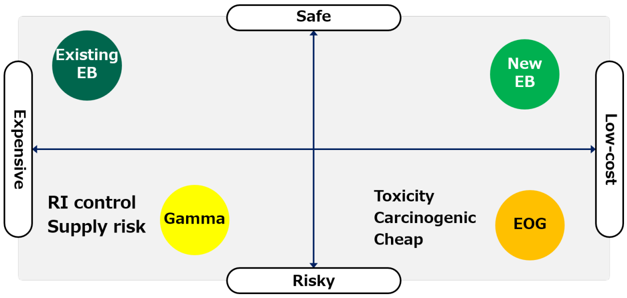

Figure 1: Currently widely used sterilisation methods are displayed on a cost (horizontal axis) and safety and risk (vertical axis) plane.

the production of radioisotopes for pharmaceuticals, as the RI produced can be controlled according to the gamma-ray energy and the irradiating element. Figure 2 shows cross-section of the photo nuclear reaction of ^{226}Ra$(\gamma,n)^{225}$Ra peaked at 10~15 MeV [9]. For the RI production, CWREB is usefull in energy of 30 MeV or more to generate gamma in the energy region by Bremsstrahlung. To understand the advantages of isotope production by photonic reactions, it is useful to compare them with nuclear reactions such as neutrons from nuclear reactors. Photo-nuclear reaction with ^{226}Ra generates ^{225}Ra, ^{225}Fr, ^{224}Ra, and ^{224}Fr. ^{225}Fr decays to ^{225}Ra with 4 min. half life, so it is equivalent to ^{225}Ra. ^{224}Ra and ^{224}Fr finally goes to ^{220}Rn with 3.7 day half life. Because ^{220}Rn is gas, it can be easily removed. In case of neutron beam in a reactor, ^{227}Ra is also produced. ^{227}Ra decays to ^{227}Ac with 42.2 min. half life. Because half life of ^{227}Ac is 21.8 years, there is no good ways to extract ^{225}Ac from the irradiated target. Waiting all ^{227}Ra decayed to ^{227}Ac, we separate Ra and Ac. Even ^{225}Ac is already produced during the irradiation, it is necessary to discard this valuable ^{225}Ac to separate ^{227}Ac. From the mixture of ^{225}Ra and ^{226}Ra, ^{225}Ac will be obtained with 14.9 day half life.

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-ray, muons, or neutrons which can be generated as the secondary particle of CWREB [10].

4K SRF GUN

The biggest problem 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, Nb_3Sn-coated SRF cavities are being investigated, because

- Higher operating temperatures (up to 4.4 K),

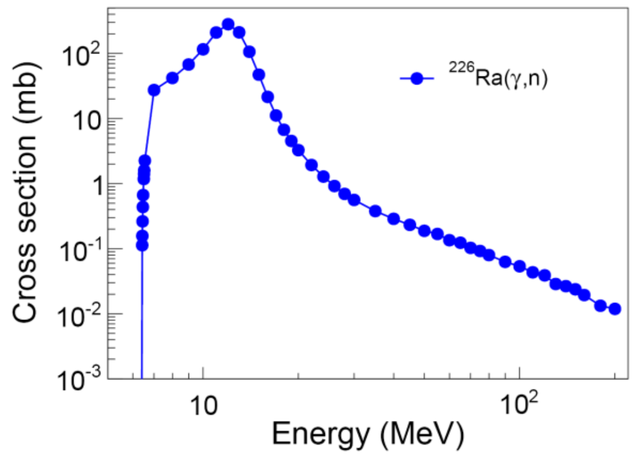

Figure 2: Cross section of ^{226}Ra$(\gamma,n)^{225}$Ra as a function of photon energy.

- Reduced surface resistance and cryogenic load,
- Achievable gradients exceeding 20 MV/m as an estimate based on demonstrated experimental values and up to 95 MV/m by employing thin layer structure [11] as a theoretical expectation.

Nb_3Sn has a critical temperature of 18 K, which is two times 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 [12].

Based on the technology of 4 K 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 [13].

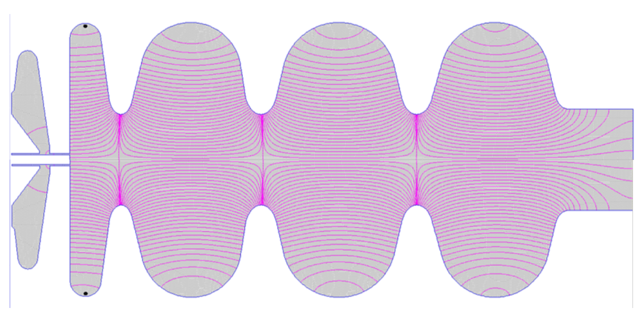

Figure 3: Cross-sectional view of the 3.5 cell SRF Gun in 2.6 GHz frequency.

The shunt impedance of the cavity was $R = 1.38 \times 10^{13}\,\Omega$/m and Q-value was $Q_0 = 4.6 \times 10^9$. With 20 W input (100 W/m), the cavity gradient becomes 37.1 MV/m and the beam energy at the exit of the gun is 5.3 MeV including the transit time factor. The Lorentz gamma factor exceeds 10 and the beam is already relativistic. The cryogenic efficiency is 0.4 % which is double of 2 K operation. Not only is the cooling efficiency high, but the difference in operating temperature between 2 K and 4.4 K is large. Since the boiling point of liquid helium is 4.2 K, cooling down to 2 K 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 2 K. Operation at 4.4 K eliminates the need for these facilities, greatly simplifying the system and reducing costs.

Q-value has a strong imapct on the operation. The Q-value is determined by BCS theory, but there is still an empirical treatment.

$$Q = \frac{G}{R_{\mathrm{BCS}} + R_{\mathrm{res}}}, \quad (1)$$

where G is the geometrical factor determined by the cavity geometry. R_{BCS} and R_{res} is BCS resistance and residual resistance. BCS resistance can be expressed as

$$R_{BCS} = A\frac{\omega^2}{T}e^{-\frac{\Delta}{kT}}, \quad (2)$$

A is a constant, ω is angular frequency, T is operation temperature, Δ is energy gap of the superconductor, and k is Boltzman constant. If we assume Δ = 1.5 meV and R_{res} = 3 nΩ for Nb, we get 1.9×10^{10} at 2.0 K which is very close to the experimental value [14]. For Nb_3Sn, Δ = 2.8 meV. If we assume 2.6 GHz and the same residual resistance, we get $Q = 4.6 \times 10^9$ at 4.4 K. If we employ lower frequency as 1.3 GHz or 650 MHz, the Q-value will be increased much, but there is trade-offs between the Q-value and the size of the system.

PHOTOCATHODE

Photocathode compatibility with SRF environments is essential. Candidates include:

- Laser cleaned Mg cathode: Clean operation (no contamination), but limited QE. To generate a large beam current, a high power UV laser (266 nm) is required.
- Cs_2Te cathode: High QE for UV light (266 nm) and a potential for high current operation, but more sensitive to SRF vacuum conditions because it is generated as a 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 with SRF cavity is confirmed [15].
- CsK_2Sb cathode: High QE [16] with green light (532 nm) excitation and robustness is high [17]. 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.

Table 1: Laser wattage to generate the required beam current. Unit is in W.

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

Nb_3Sn accelerator cavity technology has already been studied and the performance required for this proposal has already been demonstrated, so the issue is limited to technical maturity, such as reproducibility. 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.

Furthermore, when operating at high currents, regardless of the cathode material, it is necessary to overcome problems such as the effects of heat generated by the RF coupler, beam instability due to generated higher-order modes, and heat load. These issues will be studied.

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.

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.

ACKNOWLEDGEMENTS

This work is partly supported by Peace and Science Innovation (PSI) GAP FUND.

REFERENCES

[1] European XFEL Technical Design Report, DESY 2006-097(2007).

[2] "ELBE Center for High-Power Radiation Sources", Journal of large-scale research facilities, 2, A39, 2016. doi:10.17815/jlsrf-2-58

[3] "LCLS-II Final Design Report", SLAC-TN-05-035; TRN: US0503537(2005).

[4] Z. T. Zhao, H. Ding, and B. Liu, "Shanghai hard x-ray fel facility progress status", in Proceedings of the 15th International Particle Accelerator Conference, Nashville, TN (JACoW, Geneva, Switzerland, 2019). doi:10.18429/JACoW-IPAC2024-TUZN1

[5] "ILC Technical Design Report", KEK Report 2013-1(2013).

[6] J. Teichert *et al.*, "Successful user operation of a superconducting radio-frequency photoelectron gun with Mg cathodes", Phys. Rev. Accel. Beams 24, 033401, 2021. doi:10.1103/PhysRevAccelBeams.24.033401

[7] A. Arnold, J. Teichert, R. Xiang *et al.*, "Development of a superconducting radio frequency photoelectron injector", Nucl. Insr. and Meth. A 577,2007, pp 440-454. doi:10.1016/j.nima.2007.04.171

[8] Kratochwil C, Bruchertseifer F, Giesel FL *et al.*, "225Ac-PSMA-617 for PSMA-Targeted α-Radiation Therapy of Metastatic Castration-Resistant Prostate Cancer", Journal of Nuclear Medicine, 2016; 57(12):1941-1944.

[9] M. Bobeica *et al.*, "RADIOISOTOPE PRODUCTION FOR MEDICAL APPLICATIONS AT ELI-NP", Romanian Reports in Physics, Vol. 68, Supplement, P. S847-S883, 2016.

[10] M. Kuriki, T. Takahashi, H. Hayano, and S. Yamashita, "A portable muon source for artificial muon muography", presented at the IPAC'25, Taipei, Taiwan, Jun. 2025, paper TUPM080.

[11] T. Kubo, Y. Iwashita, T. Saeki, APL104, 032603(2014).

[12] S. Posen *et al.*, "Advances in Nb3Sn superconducting radiofrequency cavities towards first practical accelerator applications", Supercond. Sci. Tech. 34, 025007, 2021. doi:10.1088/1361-6668/abc7f7

[13] John H. Billen, "Reference Manual for the POISSON/SUPERFISH Group of Codes", LA-UR-87-126, 1987.

[14] A. Grassellino *et al.*, Supercond. Sci. Technol. 30, 094004 (2017).

[15] R. Xiang *et al.*, "Cs2Te normal conducting photocathodes in the superconducting RF gun", Physical Review Accelerators and Beams 13(2010)4, 043501. doi:10.1103/PhysRevSTAB.13.043501

[16] L. Guo *et al.*, "Substrate dependence of CsK2Sb photocathode performance," Prog. Theor. Exp. Phys. 2017, 033G01.

[17] M. Kuriki *et al.*, "Experimental Evidence of the High Robustness of CsK2Sb Multi-Alkali Cathode," Proc. PASJ 2017, WEOM07.