Development of the RF power distribution system for the ILC prototype cryomodule

Prakash Joshi[1,*], *Eiji* Kako[2], *Toshihiro* Matsumoto[1,2], *Shinichiro* Michizono[1,2], *Mathieu* Omet[1,2], and *Yasuchika* Yamamoto[1,2]

[1]The Graduate University for Advanced Studies (SOKENDAI), Hayama, Kanagawa, Japan
[2]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan

Abstract. The sub-local power distribution system (sub-LPDS) for the International Linear Collider (ILC) is being redesigned to satisfy the requirements. Its main features are a design with sub-LPDS within the cryomodule (CM) length, a low center of gravity, and a reduced number of waveguide components. Further, we considered to update the ILC power distribution system based on the ILC prototype design. The ILC prototype CM bunker wall's thickness will likely be limited, so a sub-LPDS with low field-emission was also designed. The sub-LPDS is planned to be mounted onto the CMs before tunnel installation at the ILC. Therefore, a prototype sub-LPDS support system was designed. A test assembly was conducted to better understand the installation process and space requirements. Furthermore, a concept of a sub-LPDS without a circulator was introduced. This concept was evaluated by analytical calculations, simulations, and low-power tests.

1 Introduction

The International Linear Collider (ILC) is a future linear electron-positron collider with a center of mass energy of 250 GeV [1]. It features two main linacs. The beam acceleration relies on superconducting RF (SRF) technology and will be realized using cavities with a resonance frequency of 1.3 GHz. The total length of the entire accelerator complex will be about 20 km, with a total length of both main linacs about 11 km [2]. In the main linacs, about 8000 nine-cell TESLA-type SRF cavities are driven in approximately 200 RF stations. The cavities will be operated using pulsed RF power with a pulse width of 1.65 ms at a repetition rate of 5 Hz. The ILC requires SRF cavities with an average accelerating gradient of 31.5 MV/m spread within ±20%.

In an RF station, there are 4.5 cryomodules (CMs) as shown in figure 1. There are two types of CMs: Type-A contains nine cavities, and type-B contains eight cavities and one superconducting (SC) quadrupole magnet at the center. A type-B CM is placed between two type-A CMs. One klystron drives 39 SRF cavities via a waveguide system called power distribution system (PDS). The RF power from the klystron is distributed into three waveguide systems called local power distribution systems (LPDSs). Each LPDS consists of three sub-local power distribution systems (sub-LPDSs). There are 13 cavities in each LPDS, and 4 or 5 cavities in each sub-LPDS (see figure 2). The variable hybrids, and variable power dividers [3] are used to realize the required power ratios.

*e-mail: prakashj@post.kek.jp

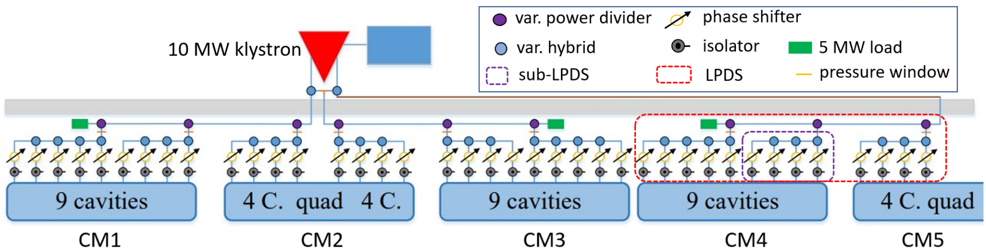

Figure 1. Schematic of the ILC PDS, highlighting the LPDS, sub-LPDS and its components [1].

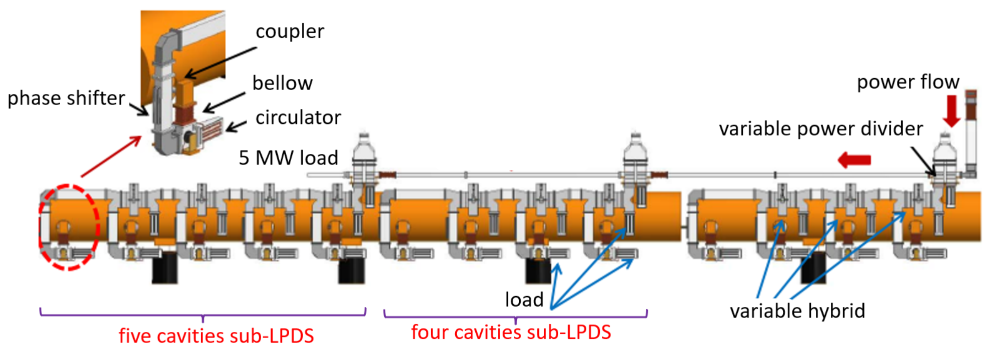

Figure 2. A model of LPDS and sub-LPDS for the ILC [1].

The sub-LPDS transmits the required RF power at the required phase to the cavities. This enables cavities to operate at the maximum operational gradient while accelerating the beam on-crest to achieve maximum beam energy. A sub-LPDS consists of variable hybrids and phase shifters [4]. While adjusting power via the variable hybrid, a phase offset is introduced, which is mitigated by phase shifter. For this purpose, a sub-LPDS was already developed at KEK [5]. This sub-LPDS was successfully demonstrated for beam acceleration at STF-2 at KEK [6].

In the main linacs, the klystron gallery and accelerator tunnel are separated by a shielding wall so that modulators, klystrons, and LLRF control racks are accessible during beam operation. The CMs already integrated with the sub-LPDS will be installed inside the tunnel. This integration and installation process is based on the experience from the European XFEL [7].

2 Redesign of the ILC waveguide system

2.1 Sub-LPDS for the ILC type-B cryomodule

The sub-LPDS for the ILC type-B CM is being redesigned (see figure 3) to satisfy the requirements. The redesign ensures the sub-LPDS fits within the CM's length for future multi-CM assemblies. The sub-LPDS was redesigned with a low center of gravity to guarantee its mechanical stability and safety. The circulators and input couplers are connected using bellows to minimize mechanical stress on the input couplers. Finally, the candidate with the lowest number of waveguide components was selected to reduce the mass and cost of the system

[8]. The redesigned sub-LPDS is an updated version of the sub-LPDS, which was already developed at STF-2.

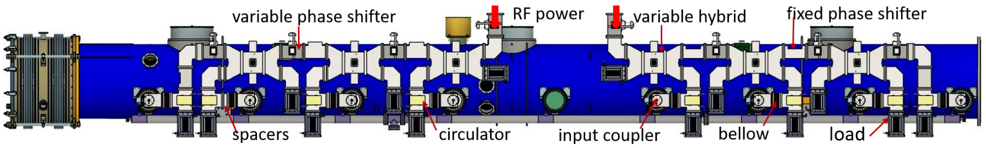

Figure 3. Sub-LPDS for the ILC type-B cryomodule [8].

In the updated version, the waveguide of the input coupler for the last cavity of each sub-LPDS is rotated to fit the sub-LPDS within the length of the CM. The length of the bellow is 100 mm due to limited space. The remotely controlled variable hybrids are used to adjust the coupling ratio. The phase offset after adjusting coupling ratio is addressed by remotely controlled variable phase shifters. To achieve an RF input phase difference of 90° in the adjacent cavities fixed phase shifters are used. This is necessary for the beam's acceleration because the distance between the adjacent cavities is 5.75λ, where λ is the wavelength of the RF in free space. They are two types of fixed phase shifters, the wide type to delay the phase, and the narrow type to advance the phase. The fixed phase shifters alone could not address the phase requirement due to their limited phase-adjusting capability [9]. Therefore, in the left side sub-LPDS (see figure 3) spacers are also used to adjust the RF input phase for beam acceleration.

2.2 Sub-LPDS for the ILC type-A cryomodule

There are two types of sub-LPDS in type-A CM. In CM1 and CM4 (see figure 1) RF power propagates from the right side to the left side (see figure 4) and in CM3 (see figure 1) from the left to the right side (see figure 5).

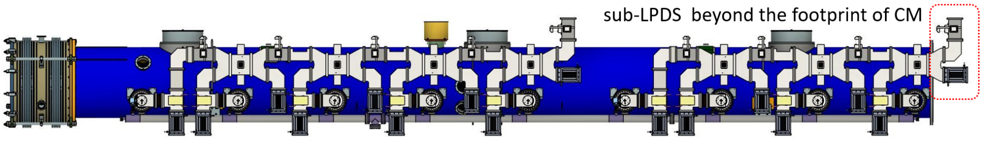

Figure 4. Sub-LPDS for the ILC type-A cryomodule (CM1 or CM4 of figure 1).

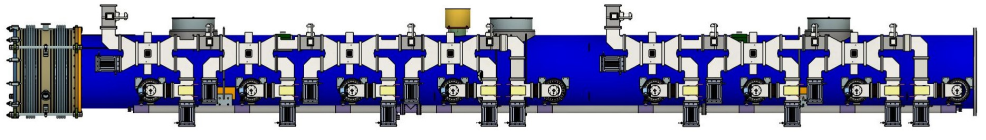

Figure 5. Sub-LPDS for the ILC type-A cryomodule (CM3 of figure 1).

The sub-LPDS model for the CM1 or CM4 extends beyond the length of the CM as shown in figure 4. This causes a conflict between waveguides and adjacent CMs. Therefore, we consider using sub-LPDS as shown in figure 5 in all type-A CMs. The fixed phase shifters shown in figure 3 and 5 are optimized for the acceleration of the beam from the right to the left side. However, fixed phase shifters are to be updated to accelerate the beam from the opposite direction.

2.3 RF unit

In the considered design, a single type of sub-LPDS is used for all type-A CMs. This requires an update of the power distribution system. Additionally, we considered the usage of two 5 MW variable power dividers at the klystron output. These dividers can adjust power and phase, while variable hybrids adjust only power. The outputs are combined with a magic tee for the LPDS-2 as shown in figure 6. When the needed power is transmitted to each LPDS, no power is dissipated in the 5 MW loads. This makes variable power dividers and 5 MW loads located at the ends of LPDSs unnecessary, so they can be removed.

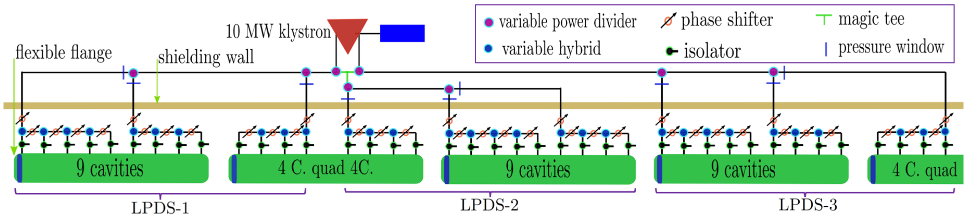

Figure 6. Schematic of a considered RF station at the ILC.

In addition, the variable power dividers and pressure windows are installed on the klystron gallery side. This allows access to the pressurized waveguide system during operation. Further, the length of the pressurized waveguides is decreased. The proposed model would require more wall penetrations compared to the previous design.

3 Sub-LPDS for the ILC prototype cryomodule

The ILC prototype CM is being developed as part of the R&D efforts of the ILC Technology Network (ITN). The ITN is jointly initiated by KEK and the International Development Team (IDT) of the ILC to execute high-priority work packages through collaboration between KEK and participating laboratories [10]. The ILC prototype CM is currently under development at KEK as part of a five-year plan [11]. It aims to mature the ILC by demonstrating the feasibility of its technologies and installation procedures. The cavities of the ILC prototype CM will be driven using the sub-LPDS system. This system will provide the necessary power and phase for the operation of the cavities.

The test bunker for the ILC prototype CM is under development. The thickness of the currently planned concrete shielding wall most likely will be insufficient due to the limited space of the test stand area. Therefore, field emission is to be suppressed. The dark current is enhanced by the acceleration of electrons in multiple cavities when the RF input phase difference in adjacent cavities is 90° [12]. If dark current is decelerated in an adjacent cavity located in one direction then it is accelerated from another direction. Therefore, the dark current emitted by one cavity passes with the RF zero crossing in the adjacent and decelerates in the following cavity. This occurs when the input phase difference between adjacent cavities is 180°. Therefore, we redesigned the sub-LPDS with the RF input phase difference of 180° among the adjacent cavities as shown in figure 7.

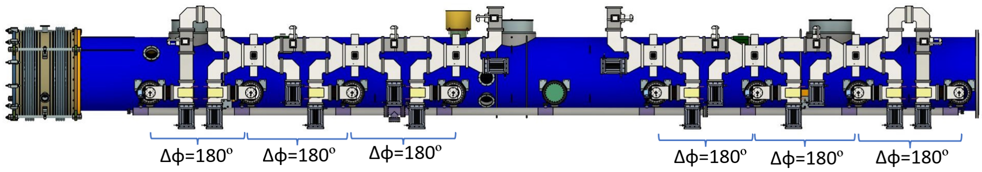

Figure 7. Sub-LPDS for the ILC prototype cryomodule to suppress the field emission.

4 Support frame prototype

Mounting the sub-LPDS inside the future ILC tunnel is not efficient due to limited space. Therefore, CMs already integrated with sub-LPDS will be installed into the tunnel. A prototype support frame was designed and fabricated to test the installation process, and to better understand the updates required for the next iteration of the support frame. The sub-LPDS was integrated into the support frame as shown in figure 8.

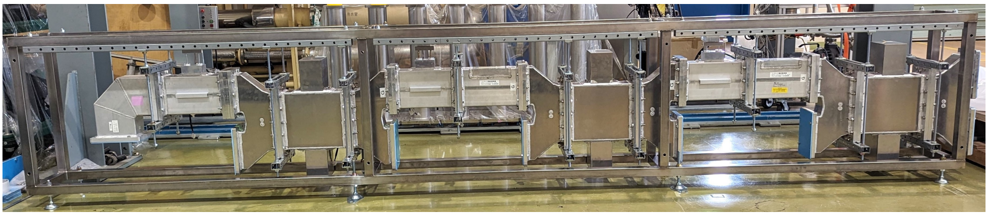

Figure 8. Integration of the sub-LPDS within the prototype support system.

5 Sub-LPDS without circulator

We are investigating the removal of the circulators [13] and dummy loads from the sub-LPDS. The motivation of removing them is to reduce the cost and mass of the sub-LPDS without compromising the safety of the klystron. Removing the circulator reduces the mass of the sub-LPDS by about 30%. In this model, the circulators are replaced with an H corners integrated with a directional couplers as shown in figure 9.

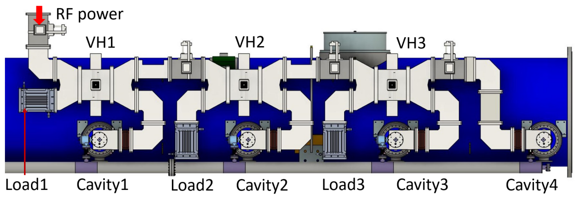

Figure 9. A sub-LPDS with circulators replaced by H-corners.

This concept was evaluated by analytical calculations, simulations, and low-power measurements. Reflected power is mostly dissipated in the loads of the variable hybrids. In four cavities sub-LPDS, no power was reflected upstream for a uniform power distribution. The reflection maxes out at about 6.5% of input power, when the reflection from odd-numbered cavities is 25% above the average and even-numbered cavities are 25% below the average, or vice versa. In the five cavity sub-LPDS about 4% of input power is reflected upstream for a uniform power distribution. A maximum of about 18% power is reflected upstream when the reflection from odd-numbered cavities is 25% above the average and even-numbered cavities are 25% below the average.

The performance of the cavities can be degraded after years of operation [14], so poor-performing cavities are detuned [15]. On detuning any or multiple cavities coupling ratios of the variable power dividers and variable hybrids are adjusted to transfer minimum power to the detuned cavities. Further, RF power reflected from sub-LPDS is partially dissipated in the dummy loads of the variable power dividers. Additionally, two circulators installed near the output ports of the klystron (see figure 10) prevent the klystron from the reflected power.

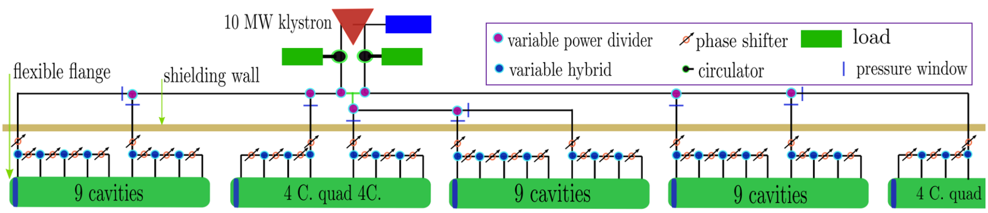

Figure 10. Schematic of an ILC RF station without a circulator in the sub-LPDS.

6 Conclusions

We considered updates in the sub-LPDS, LPDS, and PDS for the ILC RF power distribution system. The updates to the sub-LPDS are: sub-LPDS remains within the length of the cryomodule, low center of gravity, and minimum number of waveguide components. The considered updates in the ILC PDS are the usage of 5 MW variable power dividers at the output ports of the klystron, removal of the variable power dividers and 5 MW dummy loads at the end of the LPDSs, and revision of the configuration of the power distribution in sub-LPDSs. A sub-LPDS model for the ILC prototype was designed for low-field emission. A prototype support system was designed and fabricated and the first integration test was completed. Analytical calculations, simulations, and low-power measurements look promising for the removal of the circulators. On removing the circulator, RF power is partially reflected upstream, which is managed by installing two circulators at the klystron output to dissipate the reflected power.

7 Prospects

The variable power divider for the ILC power distribution system is under development [16]. The design of the sub-LPDS support frame will be revised to allow the mounting of the support frame with the sub-LPDS on the CM. The first cooldown test of the ILC prototype CM is planned in JFY 2027 [11]. The high-power test of the sub-LPDS without circulators has been considered for the following year.

Acknowledgements

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References

[1] L. Evans and S. Michizono, "The International Linear Collider Machine Staging Report", CERN, Geneva, Switzerland, Rep. CERN-ACC-2017-0097, Oct. 2017.

[2] The International Linear Collider, Technical Design Report, vol 3. pt. II, 2013, https://linearcollider.org/files/images/pdf/Acceleratorpart2.pdf

[3] C. Nantista *et al.*, "Waveguide component R&D for the ILC", *Proceedings International Particle Accelerator Conference*, Shanghai, China, 2013, pp.2881-2883.

[4] S. Kazakov, *et al.*, "L-Band waveguide elements for SRF application", *Proceedings of Particle Accelerator Society Meeting*, Tokai, Japan 2009, pp. 980-982.

[5] B. Du, *et al.*, "Development of a Local Power Distribution System for the ILC", *Nucl. Instrum. Methods Phys. Res. A*, vol. 982, p. 164589, Dec. 2020. doi:10.1016/j.nima.2020.164589

[6] Y. Yamamoto, "Achievement of the ILC milestone by beam operation of STF-2 accelerator at KEK", presented at *21st International Conference on RF Superconductivity*, Grand Rapids, USA, 2023.

[7] B. Yildirim, *et al.*, "Series production of the specific waveguide distribution for the European XFEL at DESY", *29th Linear Accelerator Conference*, Beijing, China, 2018, pp. 380-383.

[8] P. Joshi, *et al.*, "Waveguide system for an SRF cryomodule in KEK", *15th International Particle Accelerator Conference*, Nashville, USA, 2024, pp. 1492-1494.

[9] B. Du, "Development of compact local power distribution system for the International Linear Collider", *Ph.D. thesis*, SOKENDAI, Japan, 2020.

[10] "Framework for the ILC Technology Network", KEK and ILC International Development Team, Tsukuba, Japan, Jun., 2023.

[11] Y. Yamamoto, "SRF 5-year plan in Japan for ILC", presented at *International Workshop on Future Linear Collider*, Menlo Park, USA, 2023.

[12] P. Joshi, *et al.*, "Multi-cavity field emission at STF-2 accelerator in KEK", *20th Annual Meeting of the Accelerator Society of Japan*, Funabashi, 2023, pp. 572-576.

[13] T. Matsumoto *et al.*, "Operation test of distributed RF system with circulatorless waveguide distribution in S1-global project at STF/KEK", *2nd International Particle Accelerator Conference*, San Sebastián, Spain, 2011, pp. 448-450.

[14] Y. Yamamoto, *et al.*, "Stable beam operation at 33 MV/m in STF-2 cryomodules at KEK", *20th International Conference on RF Superconductivity*, East Lansing, USA, 2021, pp. 382-386.

[15] C. Schmidt, *et al.*, "Operational experience with the European XFEL SRF linac", *21st International Conference on RF Superconductivity*, Grand Rapids, USA, 2023, pp. 43-50.

[16] P. Joshi, *et al.*, "Development of a folded magic tee for the ILC power distribution system", *20th Annual Meeting of the Accelerator Society of Japan*, Funabashi, 2023, pp. 384-387.