HLRF Scheme in ILC-Toward the TDR (Technical Design Report)

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Abstract

TDR (Technical Design Report) for the ILC is being prepared now, and one of the possible HLRF scheme in ILC is changed from DRFS to DKS, which is similar configuration as the RDR. After considering the several new features of superconducting cavity performance and the new tunnel proposal, the Kamaboko tunnel, RDR-like scheme is proposed. Description of the 10 MW MBK, the Marx modulator and the common power distribution system called LPDS, is presented in this paper. Power dissipation problem is presented and comparison of power dissipation is made between KCS and DKS.

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1. INTRODUCTION

After the ITRP decision in 2004, superconducting technology was chosen to be used in ILC and then BCD (Basic Configuration Design) was summarized in RDR (Reference Design Report), based on two-tunnel configuration [1]. Aiming for the cost reduction of ILC, a single tunnel configuration and a reduced bunch operation were proposed and discussed. These results were summarized in SB2009 report by ILC-GDE in 2009 [2]. Two HLRF schemes were proposed then and Japanese team proposed DRFS (Distributed RF System), which comprised of many small klystrons system [3]. During the development of DRFS design, a few new serious features forced to revise the design; (1) degradation of superconducting cavities were found after the installation in the cryomodule and the degrading rate reached up to about 20%. DRFS needed to modify the power delivering system. (2) SB2009 proposed the reduced bunch operation and the low energy operation at the begging of the construction, and DRFS needed to be modified with a flexible manner on this upgrading pass. (3) In Asian site, tunnel boring cost was reevaluated and NATM (New Austrian Tunneling Method), which was thought to be expensive and inadequate to ILC comparing with TBM (Tunnel Boring Method), was found to be cost effective. Then, Kamaboko tunnel was proposed as the Asian site single tunnel layout. Considering the flexibility for the required reality such as (1) and (2), RDR-like HLRF scheme using the 10 MW multi-beam klystron (MBK) in Kamaboko tunnel was favored than DRFS. In Kamaboko tunnel, the thick radiation shield was possible to be constructed in the middle of the tunnel and the resultant scheme was very similar with the two tunnel configuration of RDR. This scheme was named as DKS (Distributed Klystron System) and distinguished from another single tunnel plan of KCS (Klystron Cluster Scheme). In coming TDR (Technical Design Report), DKS and KCS were chosen to be the possible HLRF schemes: the former is the scheme which was suitable in mountain side area in such as the Japan and the later is the one of flat surface area such as in USA. In this report, the introduction and technical description of DKS was presented.

2. GENERAL DESCRIPTION OF DKS

DKS is the system to use 10 MW MBK as HLRF source like the RDR and an RF power is fed to 36 superconducting cavities in the 4.5 cryomodules in baseline configuration. All required components are installed in the single tunnel of which shape is Kamaboko, the Japanese fishcake. In the center of the tunnel, 3,5m thick radiation shield is constructed. In the one side of shield, MBKs, Marx modulators, control racks and other required systems are installed with the about 2m wide aisle to install the components. In the other side, cryomodules, local power distribution systems (LDPSs) and other required components are installed. High power RF output from MBK propagates in the waveguide penetrating the radiation shield. This layout is very similar as RDR and the cross section view of this Kamaboko tunnel is shown in Figure 1.

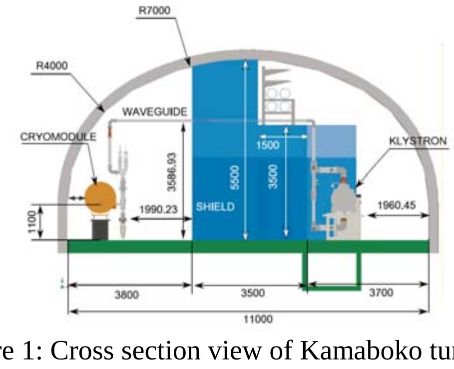

Figure 1: Cross section view of Kamaboko tunnel and layout of DKS.

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Table 1: Main linac parameter proposed in ILC

250 GeV/beam	# of bunches	bunch spacing	beam current	beam duration	rf peak power	fill time, t_i	rf pulse duration
full beam RDR	2625	369.2 ns	9 mA	0.969 ms	294.2 kW	0.595 ms	**1.564 ms**
DRFS	1313	738.5 ns	4.5 mA	0.969 ms	147.1 kW	1.190 ms	2.159 ms (up 38%)
KCS	1313	535.1 ns	6.21 mA	0.702 ms	203.0 kW	0.862 ms	**1.564 ms**
DKS	1313	553.8 ns	6 mA	0.727 ms	196.1 kW	0.893 ms	1.619 ms (up 3.5%)

In SB2009, there proposed the two operation modes called as the low power option and the full power option. In table 1, the main linac parameters in various schemes are summarized. In TDR, 6 mA operations of DKS and KCS are called as the baseline, and the operation mode corresponding to the full beam RDR is called as upgrade plan. In DKS, the baseline is the HLRF system that one MBK feeds power to 39 superconducting cavities in 4.5 cryomodules and the upgrade plan is the system that one MBK feeds power to 26 superconducting cavities in 3 cryomodules: therefore it is necessary to add more 50 % amounts of klystrons. In this report, the baseline DKS is mainly presented.

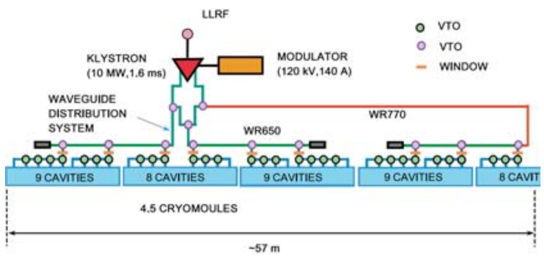


Figure 2: Layout of DKS (per an RF unit in the baseline)

Layout of DKS per an RF unit in baseline is shown in Figure 2 and the bird-eye view of the same layout is shown in Figure 3. Superconducting cavities are installed in the three cryomodules with nine, four plus quad plus four, and nine cavities respectively and these layouts are repeated. In DKS, one MBK feeds power to 39 superconducting cavities in the 4.5 cryomodules and this system forms an rf unit. As shown in Figure 2, 10MW power output from MBK is divided into

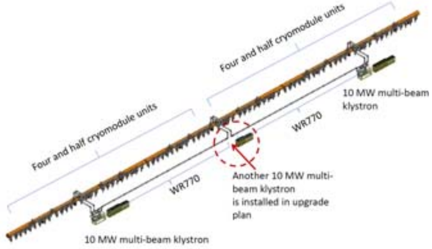


Figure 3: Bird-eye view of 6 cryomodules with two 10 MW MBKs and two LPDSs in the baseline

Figure 4: Horizontal MBK, Toshiba E3736

roughly 1/3 by power dividers and delivered to the LPDS in cryomodule side corridor. In upgrade plan, the position of red circled dash line in Figure 3 shows the place to add the extra 10 MW MBK and then 3 cryomodule forms the regular RF unit. Long waveguide line shown in Figure 3 employs the WR770 waveguide, larger dimension than usual size of WR650 in order to reduce the attenuation caused by the long propagation length.

3. HLRF COMPONENTS IN DKS

3.1 10MW MBK

In DKS, the high power RF source employs the 10 MW MBK similar with the RF source used in RDR. It has been developed for the TESLA project and European X-FEL project in DESY. Three vendors in the world competed the design and some of them were succeeded in achieving required specification. Two types of mounting layout are developed, the vertical mounting type and horizontally mounting type. The vertical MBK is planned to be used in KCS in ILC and the horizontal MBK is used in European XFEL and DKS in ILC. Vertical MBKs were evaluated mainly in FLASH/TTF and recently one MBK was introduced in SLAC and long-run operation to evaluate the life time was performed. A few tens of horizontal MBKs were procured by XFEL but it was not clear the operation detail so far. KEK procured a 10 MW horizontal MBK and is preparing to operate it. In table 2, specifications of 10 MW klystron is shown. In Figure 5, an MBK characteristic of an output power and efficiency with the function of an applied voltage is shown, which was

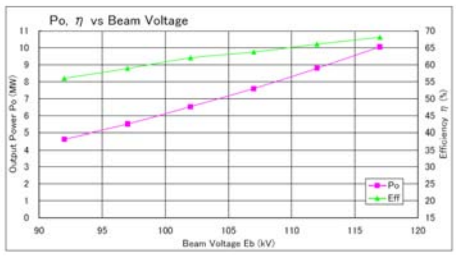


Figure 5: Characteristics of MBK, an output power and efficiency with the function of applied voltage.

measured with the MBK of SLAC.

Manufacturing procedure of MBK at the construction period of ILC strongly depends on the klystron cost and HLRF team discussed with klystron vendor to achieve the cost efficient manufacturing. For the manufacturing of klystron, not only manufacturing but also processing of the tube is required. Manufacturing processes needed

Table 2 : 10 MW Klystron Specifications

Parameter	**Unit**	**Specification**
Frequency	MHz	1300
Peak power output	MW	10
Rf pulse width	ms	1.616
Repetition rate	Hz	5
Average power output	kW	78
efficiency	%	65
Saturation gain	dB	>47
Cathode voltage	kV	<120
Cathode current	A	<140
Micropearveance	$mA/V^{1.5}$	3.38
Lifetime	hr	>50000

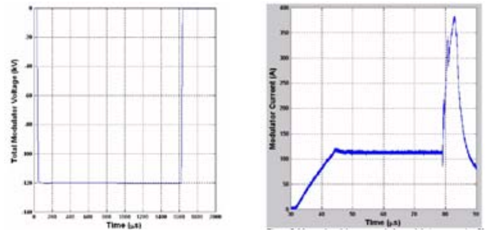
the expensive facilities such as brazing furnaces and evacuation/baking furnaces. Processing process required the pulse modulators and processing of about two and half week long is required per one tube as a usual process. In ILC construction, about 400 MBKs are manufactured in 5 years period, and therefore investment for several furnaces and modulators results in more expensive cost. In order to reduce such an investment cost of the vender, ILC-GDE considers the introduction of hub-institute system. Large institutes such as the KEK and SLAC offer the test facility equipping several modulators to proceed the processing of the tubes. After completion of manufacturing, used modulators are returned to ILC to use them as the regular modulators. By introducing this system, cost reduction is possibly achieved. Cost of 10 MW MBK is estimated using this idea.

(a) (b)

Figure 6: (a) Marx modulator of DTI (b) P2 Marx of SLAC

3.2 Marx Modulator

Pulse modulator for the 10 MW MBK in RDR was combination of the IGBT pulse modulator with a bouncer circuit and 1:12 pulse transformer. While the current modulator for MBK is a Marx modulator. Its advantages are as follows; (1) fast rising and falling time of the pulse, (2) direct connection of 120 kV to the MBK without using a pulse transformer, (3) good flat top in the pulse by the timing adjustment of the low voltage Marx module, and (4) fast shut down when the



(a) (b)

Figure 7: (a) output pulse waveform from P2 Marx (b) Snapshot when load was arced

load is arced.

P1 Marx had been developed in SLAC since 2007, and after the completion of P1 Marx successively, P2 Marx was started to manufacture. P2 Marx was completed in the end of 2012 and excellent performances were reported [4]. On the other hand, the Diversified Technologies INC (DTI) in USA got the budget from DOE and manufactured the compact Marx. All Marx units are immersed in the insulation oil vessel and showed the excellent performance. In Figure 6, the photos of DTI Marx and SLAC P2 Marx are shown. In Figure 7, waveforms of P2 Marx are shown. Pulse waveform of output from Marx and the snapshot waveform when the load is arced are shown in Figure 7. Very fast rise and fall time of the pulse of 10 μs are obtained and flat top flatness of +/-0.05% are achieved when pulse width modulation (PWM) portion of the cells are staggered. In Figure 7 (b), performance when arc occurs in the load is shown. It shows that at ~78μs a self-break spark gap across the load closes. Table 3 shows the Marx cell and modulator parameters.

Table 3: Marx cell and modulator parameters

Items	Specifications
Cell Weight	<50lb
Cell Dimensions (WxDxH)	13.75”x29.5”x8”
Cells per Modulator	32
Minimum Cells for Pull Output	30
Modulator Dimensions (WxDxH)	9’x5’x8’

3.3 Power Distribution System (PDS)

Basically PDS is similar with the RDR, while from a few reasons, modified PDS is employed in DKS. (1)Tough in RDR the superconducting cavities are

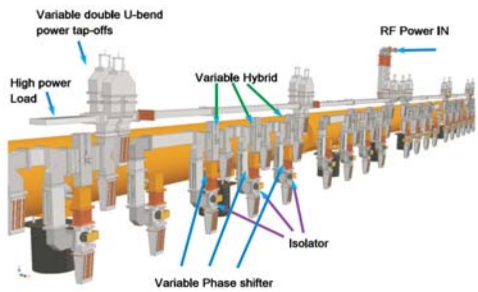


Figure 8: 3D view of Local Power Distribution System

assumed to have all the same characteristics (the same Q value and the same field gradient), but it was found that the cavity performance variations are large and furthermore the cavity performance degradation after installing to the cryomodule was also found. In order to optimize the cavity performance, it is necessary to introduce the mechanism of the Ql variation and the input power variation to the cavity. Former is achieved by the coupler tuner and latter is realized by introducing the variable power divider. (2) At first PDS of two schemes, DKS and KCS, used different PDS, while since superconducting cavity and cryomodule are common, the same PDS near cryomodule is desirable. This is achieved and common LDPS is introduced. (3) For the selection of the waveguide components, both the function and the cost effect are considered. (4) Except for the LPDS, two schemes use the own power distribution system. Schematic drawing of LDPS are shown in Figure 2 and 3D pictures are shown in Figure 8.

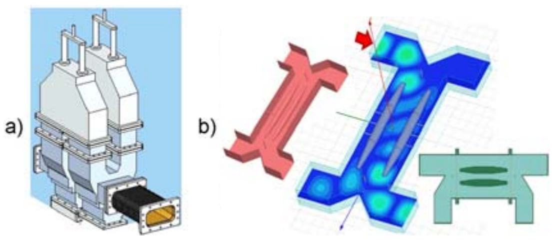


Figure 9: Tap-offs or variable hybrid (a) tap-offs with two folded magic-T's and two U-bend phase-shifters (b) variable H-hybrid with two moving conductor

In LPDS, there used the two type of variable power divider. One is used in high power line which the waveguide inside is pressurized in 2 to 3 atmosphere pressures. Variable tap-offs with two folded magic-T's and two U-bend phase-shifters designed by C. Nantista is employed [5][6]. Near to the cryomodule, downstream of a rectangular RF window, waveguide inside is an atmosphere pressure since the RF power level is less than 1 MW. Here the variable H-hybrid which has the two floating movable conductors in the interaction region are used, which was developed by V. Kazakov. It is cost effective but when power is changed, the phase from the port is changed and another phase-shifter to compensate the phase-shift is required. Two types of variable power dividers are illustrated in Figure 9. In Figure 10, a klystron power system is illustrated

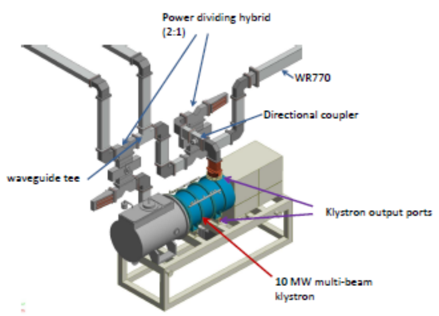


Figure 10: Klystron power system

One of the important tasks on PDS in ILC is how to install the LPDS in the tunnel during the construction period from the cost and construction efficiency viewpoints. From this viewpoints, it is desired that LPDS should be pre-assembled at the different place other than the tunnel. If possible, cold measurement of LPDS is desirable in the pre-assembling area. For LPDS preassembling, there are two different ideas. One is that parts of LPDS are assembled on the certain frame at the different area, and then conveyed to cryomodule area in the tunnel and the assembly is anchored in the tunnel. In this case, still connection of waveguide flanges and the couplers are necessary and there are certain amounts of labor. Another idea is parts of LPDS are preinstalled to the cryomodule by making use of the support attached on the surface of cryomodule. In this case, very small labor work is allowed in the tunnel. Since there are no realistic mechanical designs about the support from the cryomodule, further work should be progressed. Though LPDS is different, X-FEL project employs this approach and it is worth value to pay attention to this direction. Concerning with this approach, since the installation group in ILC is in charge of all installation, HLRF team is collaborating with them for the LPDS preassembling issues.

4. POWER AND HEAT LOSS COMPARISON AMONG DKS AND KCS

As described before, in SB2009, the single tunnel plan is proposed to reduce the cost and two schemes are introduced; the KCS which has all RF source facilities on the surface, and the DKS, the all required components are installed in the single tunnel. From the civil cost, the latter has an advantage in cost and is an inevitable scheme in the mountain region like in Japan. On the other hand, for the cooling cost due to the heat losses generated in the tunnel, KCS and DKS show the large difference. In this section, power and heat loss requirements are considered.

Energy to accelerate the beam is supplied by klystron as the RF power and it is delivered through the waveguide. The efficiency to generate the RF in the klystron is 65%, and remainder is consumed as heat loss. Since the efficiency of the modulator to supply the power to klystron is not 100%, heat loss is generated. RF powers other than the one which was used to beam acceleration are basically reflected from the cavity and dissipated in the dummy load of the circulator. In KCS, the heat losses are dissipated both in the surface and the tunnel. In surface the heat dissipation is not difficult compared with the tunnel heat loss. In DKS, since all components are installed in the tunnel and as the result, all heat losses are dissipated in the tunnel and cooling load is very large. Cooling of the water or air is required and this cost should be considered.

Total power from the wall plug, the power dissipated by the beam acceleration and the rest of the power which is corresponding to the power which should be cooled are illustrated in the bar graph in the case of KCS and DKS in Figure 11. In KCS, the powers which should be cooled are distributed in surface region and in the tunnel region, and fraction of this part is also illustrated in the figure. In KCS, combined RF power generated by the 30 clustered klystrons are propagated through the low loss circular waveguide, but still the loss is large, and the required total numbers of klystrons are larger than the DKS case by amount of ~10%. Therefore total power from the wall-plug is also 10% larger than that of DKS. So KCS cost of components is higher than DKS. From Figure 11, the power dissipation in the tunnel which should be cooled in DKS is higher than KCS by amounts of more than 200%. Cooling cost in the tunnel is expensive and from this view point, DKS cost is higher. It is not obvious to judge which is higher cost between DKS and KCS comparing of the construction cost or the operation cost including cooling cost, but it gives us the clue to reduce the cost. For the case of cooling system design, LCW (Low Conductivity Water) cooling system is high cost, and it is desirable to choose another way if possible. Air conditioning cost is also higher cost than water cooling, and it is necessary to use the water cooling as possible as we can. Water cooled rack and cabinet are recommended to reduce the cooling cost. By using these data, CFS (Civil Facility System) team has an effort to make the cost optimum design.

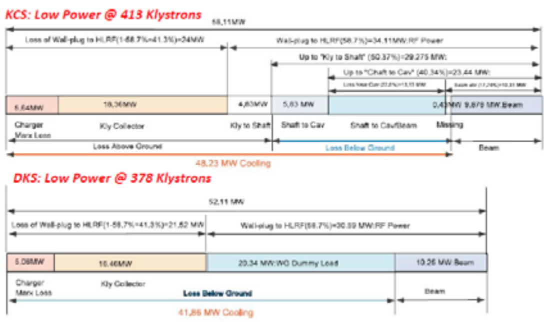


Figure11: Power consumption comparison between KCS and DKS.

5. DKS TEST IN KEK.

KEK has the test facility called as STF (Superconducting RF Test Facility) and evaluates the technical items of ILC. We have been testing the technology based on the HLRF of RDR and DRFS. Especially in the S1-global test, which was international collaboration, HLRF showed the successful results based on RDR and DRFS. Since DKS is approved as the possible HLRF technology scheme, we should have an effort to test the HLRF based on the DKS.

High power horizontal MBK, Toshiba E3736, was procured in FY 2010. Since the test of DRFS had a priority in FY2011 and FY2012, we did not use the 10 MW MBK, and we have a plan to use it for coming STF-II, the similar configuration as S1-global with a beam acceleration.

For the Marx modulator, SLAC has been studying it since 2007. For this direction, since KEK concentrated to develop the IGBT modulator with bouncer and modulation anode modulator with DC power supply for DRFS, we are behind the SLAC. Japanese vendors are not matured to manufacture the Marx immediately. While in 2012, we had a chance to use the DTI Marx with the kind offer by the SLAC, and we have a plan to use it for the STF-II project.

Concerning with the LPDS, we have many components which are possibly used in DKS. LPDS shown in Figure 8, the technology and components are combination of design of SLAC and KEK. For the components developed in SLAC, we try to introduce the design and evaluate the device in STF-II. For isolator manufactured in Japan, there are some trouble reports and we try to solve these troubles.

LLRF technology is not described at all, but LLRF technology is as important as HLRF. Though HLRF scheme is changed from DRFS/RDR to DKS, the technology of the LLRF remains same.

6・ SUMMARY

DKS, which is approved as the one of HLRF scheme which is used in the mountain site topography, is reported. In TDR (Technical Design Report), which is completed in the end of 2012, DKS is described. In KEK, DKS system will be evaluated in the phase of STF II and we try to show the feasibility of the DKS.

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