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TITLE: SYSTEM FOR SAVINGS 6 MW of SLC RF SYSTEM LINE POWER

This note describes a system that enables us to reach the required 21 MV/M SLC gradient with 40 MW - 5 μ s klystrons. It requires a superconducting 2.5 μ s microwave delay line (MDL) to be installed in series with the existing SLED network, but can save up to 6 MW of site line power.

Figure 1 illustrates the system schematically. The outputs of two klystrons, K1 and K2 are combined in the hybrid H. During the first half of the pulse, the phase $\Phi 1$ is such that the combined output of the two klystrons exits port 3 of hybrid H and fills the MDL with rf. At $t = 2.5 \mu$ s, we flip $\Phi 2$ by 180° , so that during the second half of the pulse the combined output of K1 and K2 exits port 4 of the hybrid H. The result is two, simultaneous, 80 MW - 2.5 μ s pulses, which are transmitted to the existing SLED networks. In order for these pulses to be further compressed so as to obtain the 1.4 SLED gain expected for a 2.5 μ s pulse, the pulses have to be properly modulated. This is accomplished with phase shifter $\Phi 1$, which presently precedes the sub-booster input, and which has had its driving pulse slightly modified. The phase across both $\Phi 1$ and $\Phi 2$ as a function time are also shown in Fig. 1.

The ac line power is obtained as follows. The modulator line power required to generate 40 MW - 5 μ s rf is 26.1 MW. To this we must add the equivalent refrigerator power required by the MDL. The rf energy/pulse dissipated in the MDL is

$$U_d = U_k(1 - e^{-2\tau}) = P_k T_p(1 - e^{-2\tau}) \quad (1)$$

Using the fact that $\tau = \omega T_s / 2Q$ and is much less than unity, we have

$$U_d = P_k T_p 2\tau = P_k T_p \frac{\omega T_s}{Q} \quad (2)$$

The average power dissipated in the MDL is

$$P_d = P_k T_p N_{pps} \frac{\omega T_s}{Q} \quad (3)$$

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Fig. 1. Pulse compression system for 5 μs klystron, 2.5 μs SLED pulse.

where

- U_k = klystron output energy/pulse
- P_k = klystron peak power
- T_p = klystron pulse width
- r = MDL attenuation in nepers
- T_s = MDL filling time
- Q = unloaded Q of MDL cavities
- N_{pps} = Number of pulses per second

The MDL can be made up of coupled cylindrical or spherical cavities oscillating in the TE_{011} mode, with an unloaded Q of 60000 if made of copper. If the MDL is made of niobium cooled to 4.2° we obtain an improvement factor of 4000. As T_s is $2.5 \mu s$ and Q is 2.4×10^8 , the average power dissipated in the MDL at 180 pulses/second is 6.7 watts.

Now let the length of the MDL be 2 meters and fold it as shown in Fig. 2, so that it can be accommodated in a short cryostat. The total amount of line power needed by the refrigeration equipment to remove 8 watts of dynamic and static heating is 14 KW at 4.2 K and considerably less for a possible 12 K operating temperature with Nb_3Sn cavities. Four refrigerated MDL sections are required per sector, or 120 in all, which gives us a total power requirement of 1.7 MW to satisfy the refrigeration needs. Note that this number includes a generous allowance for peripheral equipment. Thus the total line power needed is $26.1 + 1.7 = 27.8$ MW. Compare this requirement with the 32.3 MW of modulator line power plus 1.2 MW of klystron focusing magnet power, or a total of 33.5 MW required by the 50 MW - $5 \mu s$ system. The saving is thus almost 6 MW, or at \$0.087/kWhr about \$500 for each hour the system is operated.

The increased efficiency is due to the increase in SLED efficiency as we halve the pulse length. The ac to rf efficiency is not reduced due to rise and fall time because the klystron pulse length remains unchanged at $5 \mu s$.

The group velocity is $2/2.5 = 0.8$ m/ μs . If the MDL cavities are right circular cylinders the length of each is 0.14 m and the loaded Q which is also the external $Q = \omega L/v_g = 3140$. The time constant of a single cavity $T_c = 2L/v_g = 0.35$, and this may have to be lowered.

Fig. 2. Physical layout of the pulse compression system.

Another interesting way to apply the above described system is to leave the klystron pulse width at $2.5 \mu\text{s}$, and halve the accelerator section filling time to $0.41 \mu\text{s}$. The efficiency will increase 28% due to reduced section losses and 8% due to reduce cavity dissipation, a total increase in efficiency of 37%. Because the MDL filling time is only $1.25 \mu\text{s}$ the refrigerator power is half that for the previous system. The cost of refrigerator and MDL, probably, does not exceed that of the extra capacitors and modulator modification. The decrease in section filling time can be accomplished either by increasing their group velocity or cutting them in two. Increasing the group velocity can be charged to the reduction of beam loading enhancement factor.

Conclusion

We present here a system which improves both the ac and rf to accelerating energy efficiency, and which can be used as a backup to or enhancement of the of the 50 MW - $5 \mu\text{s}$ klystron. True, the superconducting MDL represents a barrier to be overcome, but so does the change from a permanent magnet to an electro-magnet for the new klystron. This system also avoids the rf window breakdown problem and the possible melting of the indium in the rf valves. We believe the specifications for the MDL are attainable and the system can be developed in parallel with the 50 MW - $5 \mu\text{s}$ klystron and if both are successful the results can be used in series.

If we combine the output of the MDL and the output of port 4 of the hybrid in an additional hybrid we have a single stage of a "Power Doubler," which almost certainly will be needed for super-SLC, and which is the subject of another note.

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