Superconducting RF Cavities and a 1.9 K Cooling System for a Femtosecond Light Source*

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***Abstract*— The proposed femto-second light source consists of a re-circulating linac that delivers an electron beam to an arc of superconducting undulator magnets that deliver very short pulses of x rays to materials science experiments. Superconducting RF cavities accelerate the electrons through the re-circulating linac. The design acceleration gradient for the 1300 MHz RF cavity system is 25 MV per meter. TESLA cavities operating in CW mode can provide this level of acceleration. This report presents the parameters of the proposed femto-second light source superconducting linac. Each nine-cell cavity will generate 44 W of AC loss at 1.9 K. The AC loss is added to the other losses in the accelerator cavity system. The superconducting RF cavity losses and linac refrigeration requirements are summarized in this report.**

***Index Terms*—Superconducting RF Cavities, CW Operation, Super-fluid Helium**

. INTRODUCTION

Our proposed x-ray facility[1] has the short pulse length necessary (~60 fs FWHM) to study very fast dynamics, high flux (approximately 10^{10} photons/sec/0.1%BW) to study weakly scattering systems, and tuneability over 1-10 keV photon energy. The repetition rate of 10 kHz is matched to the requirements of the experimental sample or the attendant pump laser systems for structural dynamics experiments. The machine accommodates seven 2m long undulators, and six 2T field dipole magnets each with a 60 mrad arc angle.

A re-circulating superconducting linac is used for acceleration of electrons produced by a high-brightness photo-cathode RF gun, at a bunch repetition rate of approximately 10 kHz. The system design produces a small vertical emittance, which is key to producing the ~60 fs x-ray pulses from the electron pulses of ~2 ps duration.

A femto-second synchrotron radiation source can produce a much brighter x-ray beam than can pulsed light sources that are derived from lasers. A synchrotron light source based on an electron beam with an energy of 2.5 GeV can produce short pulses of x-rays with near maximum brightness in the range of photon energies from 0.3 keV to 10 keV, when the undulator and dipole bending fields are of the order of 2T.

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II. THE PROPOSED LBNL LIGHT SOURCE LATTICE

The proposed femto-second light source will be a 2.52 GeV re-circulating linac that uses 40 TESLA Cavities to accelerate the electrons from 10 MeV to 2520 MeV [1],[2]. The pre-acceleration is done using a 10 MeV RF gun and a 110 MeV TESLA cryogen module that contains 8 cavities that operate at an acceleration gradient of about 15 MV per meter. The pre-acceleration section is the innermost ring shown in Fig. 1.

The beam from the injection linac goes into a 600 MeV linac that uses four TESLA cryogenic modules with thirty-two TESLA cavities operating at a peak gradient of 25 MV per meter. The electron beam is re-circulated through the four-module linac until the final beam energy reaches 2520 MeV. The beam energy at the end of each of the stages is 720 MeV, 1320 MeV, 1920 MeV, and 2520 MeV. The four outer rings shown in Fig. 1 are re-circulator rings.

A beam spreader directs the electron beams at the four energies into their respective rings for the next round of acceleration. The beam combiner reconciles the four different energy orbits into a single line that passes through the four-module linac. The beam spreader and beam recombiner is fabricated using conventional magnets. Hence, they will not be described any further. For more information see [1] [3]. The details of the spreader and recombiner are not shown in Fig. 1.

The magnetic arcs transport the electron beams at different energies from the end of the spreader to the back straight section and from the back straight section back to the recombiner. The arcs are comprised of three 60-degree bends with straight sections between them (see Fig. 1).

All straight sections are FODO lattice sections that match with the arcs. Physically the straight sections contain four pairs of focusing and de-focusing conventional quadrupoles. These magnets are not described further in this report.

The synchrotron light production section consists of six triple bend cells with an arc angle of 6 degrees per cell. Two short modules of seven TESLA RF cavities are located between the last arc bend and the synchrotron light source region. The cavities, which are driven in the first dipole mode, are used to shorten the electron beam length before it passes into the light production zone [4]. The synchrotron light is produced by the six bend sections and seven superconducting undulator magnets that are 2-meters long.

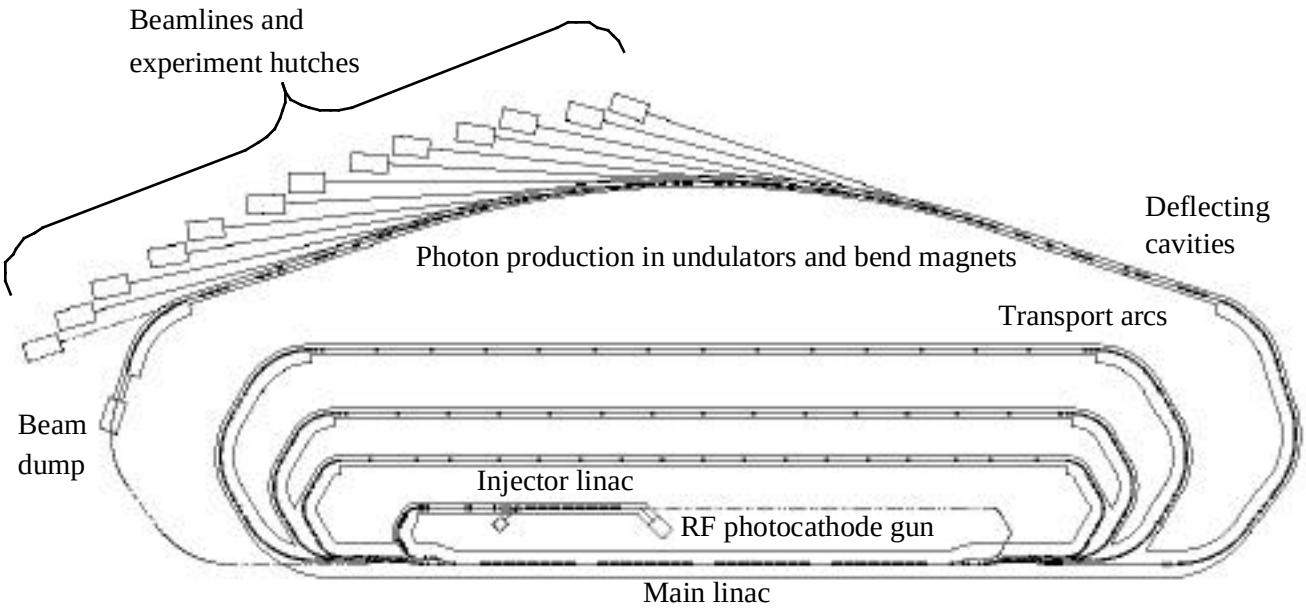

Fig. 1. The re-circulating Linac used for the production of 100 femto-second Pulses of Synchrotron Light.

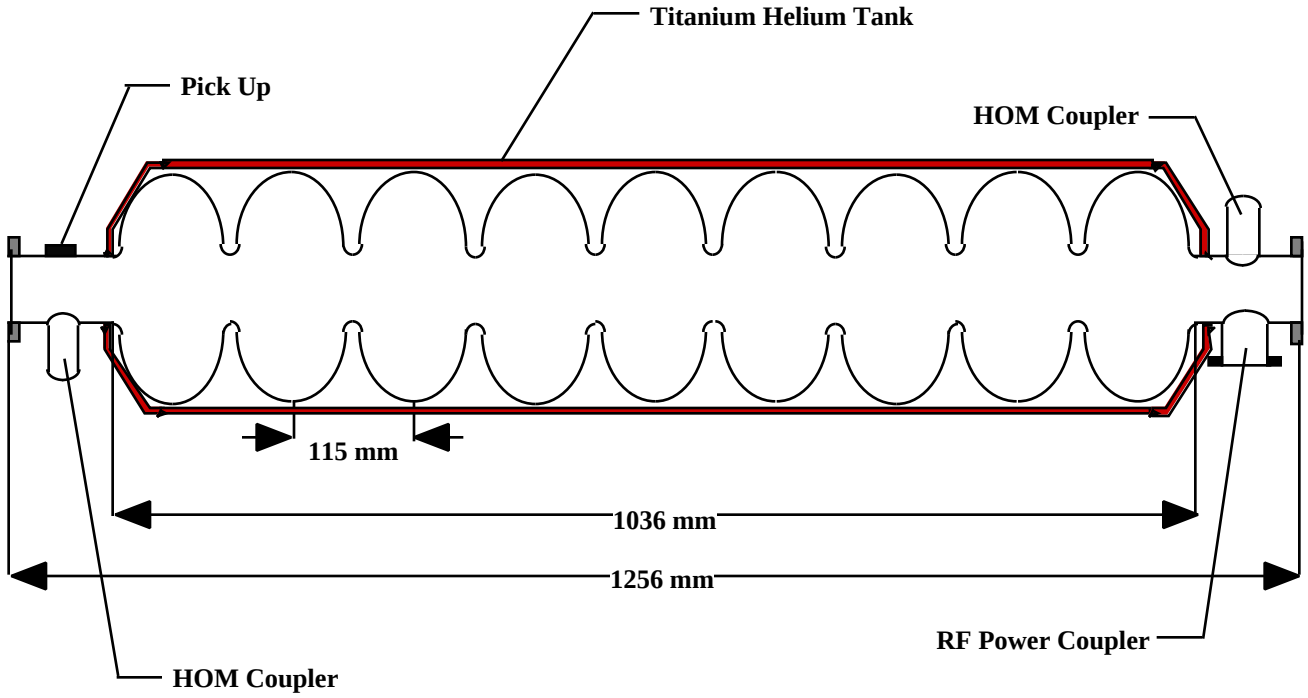

Fig. 2. A Longitudinal Section of a TESLA Nine-Cell Superconducting RF Cavity Capable of 25 MV per Meter Acceleration.

III. The Proposed TESLA Cavity and Cryomodule

LBNL proposes to use the superconducting RF cavities that have been developed for the TESLA colliding beam facility proposed by DESY. The TESLA superconducting RF cavity shown in Fig. 2 has nine cells tuned to 1.3 GHz. Each cavity section is within a titanium helium tank, which has been modified to produce extra clearance around the niobium cavity. The extra clearance is needed to transport the 44 W of AC loss heating during CW operation from the niobium cavity to the surface of the super-fluid helium where boiling occurs. Continuous operation of the TESLA cavity has been achieved with a cavity gradient of 25 MV per meter and a cavity Q that is greater than 10^{10}. CW operation of the TESLA cavities for the fast pulse light source looks very promising.

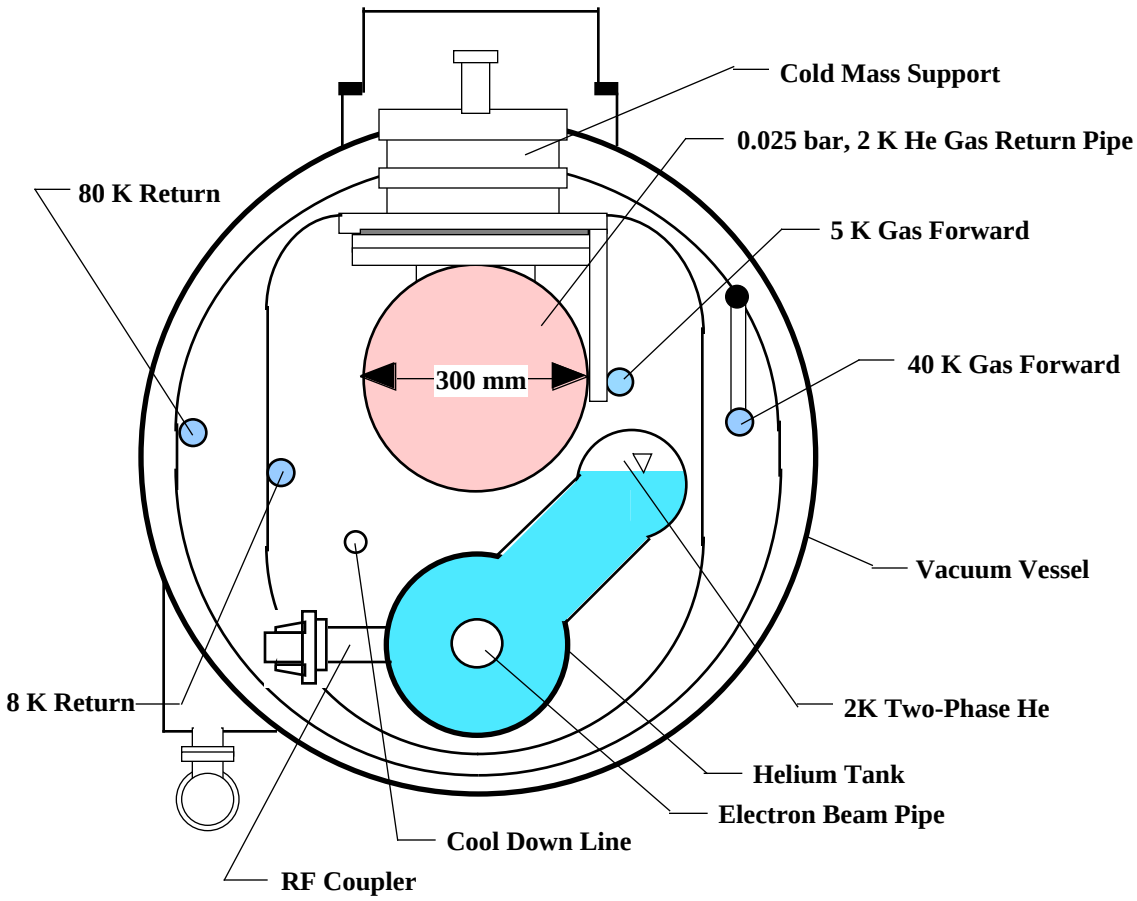

Fig. 3. A Cross-section View of a Modified TESLA Cryogenic Module. This section shows the location of the cryogen feed to the helium tank, the 1.9 K low pressure return pipe, the shield cooling pipes, the RF coupler, and cool down piping.

A cross-section of the modified TESLA cryogenic modules for eight cavities is shown in Fig. 3. The header pipe that carries two-phase helium II must have its cross-sectional area increased by a factor of two over that shown in the TESLA design report [5]. The cross-section must be increased in order for it to be able to carry that added AC loss heat load due to CW operation of the cavities. In addition, the super-fluid helium standpipe between the two-phase helium header and the helium tank must have its cross-sectional area increased by a factor of two in order to carry the extra AC heating from the cavity.

The gas phase from the two-phase header pipe is carried back to the refrigerator cold box by the 0.025 bar, 2 K return pipe shown in Fig. 3. The low-pressure return pipe diameter is shown as 300 mm. This diameter may be reduced somewhat to say 250 mm, because there are only four cryogenic modules in the linac and the distance to the return side of the refrigerator is rather short (of the order of 120 m).

Fig. 3 shows intermediate temperature cooling at 5 K and 40 K. The 5 K cooling intercepts heat going into the RF cavity from the RF coupler. The gas in the 5 K circuit is returned to the refrigerator cold box at 8 K. The 40 K helium is used to cool the cryogenic module shield and remove AC losses entering the cryogenic module through the coupler. The gas that enters the cryogenic module at 40 K returns to the cold box at a temperature between 65 and 80 K. The heat loads at 1.9 K, 5 K, and 40 K are dominated by the AC losses due to CW operation of the RF cavities.

IV. Acceleration Cavity Cooling

The cavity operating temperature has been set to be 1.9 K in order to maximize the cavity Q. The BCS limit on cavity Q falls rapidly as the temperature rises above 2 K. As a result, at 4.5 K, the cavity Q would be a factor of twenty lower than it is at 2 K. Since the AC loss heating dominate the cavity heat load, the refrigeration needed to cool 4.5 K cavities would be larger than the refrigeration needed to cool 2 K cavities. Below 1.8 K, the cavity Q will continue to get larger, but cavity performance will be limited by the heat transfer from the cavity to the super-fluid helium. The refrigeration needed to cool the light source RF cavities is summarized in Table I.

TABLE I
THE HEAT LOADS FOR VARIOUS CAVITY SECTIONS

Component	Pre Linac	Main Linac	Deflectors
Cavity AC Losse (W)	199	2138	397
Static Load at 2 K (W)	~1	~7	~2
Total 2 K Heat Load (W)	200	2145	399
AC Loss at 5 K (W)	76	326	112
Static Load at 5 K (W)	10	40	9
Total 5 K Heat Load (W)	86	366	121
AC Loss at 50 K (W)	1880	17918	508
Static Load at 50 K (W)	67	267	58
Total 50 K Heat Load (W)	1947	18185	566
Equivalent Refrigeration at 4.5 K		8.31 kW	

As one can see in Table I, the heat load at all temperatures is dominated by the AC losses in the cavity and the couplers leading to the cavities. Over eighty percent of the static heat loads is taken up in the shields that are supplied with 50 K gas from the refrigerator. The largest heat load at all temperature is taken in the four cryogenic modules of the 600 MeV acceleration section. The AC losses per unit length are much larger in this section because the acceleration gradient is large. The pre-acceleration linac and the deflector cavities have a much lower acceleration gradient. For a given cavity Q the AC loss heat load in the cavity goes up with the acceleration voltage squared. At an acceleration gradient of 25 kV per meter, the measured Q of the cavity is about 1.3×10^{10}, which means that there is not a lot of margin in the cavity performance.

There is room in the acceleration straight section for an additional cavity cryogenic module. The use of an additional TESLA cryogenic module will reduce the overall equivalent 4.5 K refrigeration to 6.9 kW. One can balance the cost of refrigeration with the cost of the extra TESLA cryogenic module. When one accelerates with five TESLA modules instead of four, the operating margin in the acceleration section would be larger because the design cavity Q is farther from the BCS limit for cavity Q at 2 K. The size of the refrigeration plant for the LBNL femtosecond light source is equivalent to one of the three 8 kW cryogenic plants that supply 4.4 K cooling to HERA [6].

The refrigeration plant must be carefully designed for combined operation at 1.9 K, 5 K and 50 K operation. The return line through the acceleration sections and to the refrigeration cold box must be large enough so that the pressure drop is low. The refrigerator will most certainly use cold compressors so that the pressure drop through the refrigerator heat exchanger is not a limiting factor. The cold compressors will reduce the number of stages of compressor on the room temperature side of the plant, but they do not improve the overall cycle efficiency significantly. The input power to the refrigerator and the cooling towers to cool the compressors while the refrigerator is operating under its design load is estimated to be about 3.3 MW. This is based on a refrigeration efficiency of 22 percent of Carnot [7] [8].

V. CONCLUDING COMMENTS

The LBNL studies show that TESLA niobium cavities can be used for beam acceleration and deflection in the femto-second light source. The use of the TESLA cavities reduces the size of the light source and its overall electric power consumption. Superconducting RF cavities are essential for this type of light source on the LBNL site.

The TESLA cryogenic module must be modified so that the AC loss heating can be removed from the cavity helium tank. The added AC losses require that the cross-sectional area of the two-phase helium feed pipe and the standpipe between the two-phase feed pipe and the helium tank be increased. The RF coupler that feeds RF to the cavity must allow for cooling of the room temperature part of the coupler. It appears that the changes needed can fit into the cryogenic module that was designed by DESY for TESLA.

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