10. The 200 and 400 MHz High Power RF Systems

10.1 Introduction

In the neutrino source the largest number of high power rf systems is required in the cooling channel itself. Ionization cooling of muons requires strong solenoidal magnetic fields and the cavities, which replenish the energy loss in the absorbers, have to be placed inside. Overall this leads to a complex technical layout which includes magnets, absorbers, cavities and diagnostics together with cryogenic feeds, high power rf couplers and water for cooling the structures. A typical layout under study for the cooling channel is shown in Figure 1 where superconducting coils surround the normal conducting cavities. This cooling channel is approximately 150 meters long and requires more than 75 klystrons. The total installed voltage is approximately 2 GigaVolts. The geometric layout of the klystron gallery for the cooling channel has been worked out in much greater detail than for the superconducting accelerator, because the high density of rf power sources makes the building, the installation, and the maintenance a challenge. The general facility requirements for the klystron gallery of the superconducting accelerators are scaled from the cooling channel gallery.

For the superconducting accelerators, 200 and 400 MHz power sources are required. While the pulse length here is much longer, the total number of klystrons required to accelerate the beam from 0.1GeV to 50 GeV is less than in the cooling channel. In this case many cavities are powered by a single klystron station. The pulse length of the klystron is much longer because the cavities are filled over a much longer period of time (compared to the Muon Accelerator Driver in chapter 7).

10.2 Considerations and Specifications for the Cooling Channel

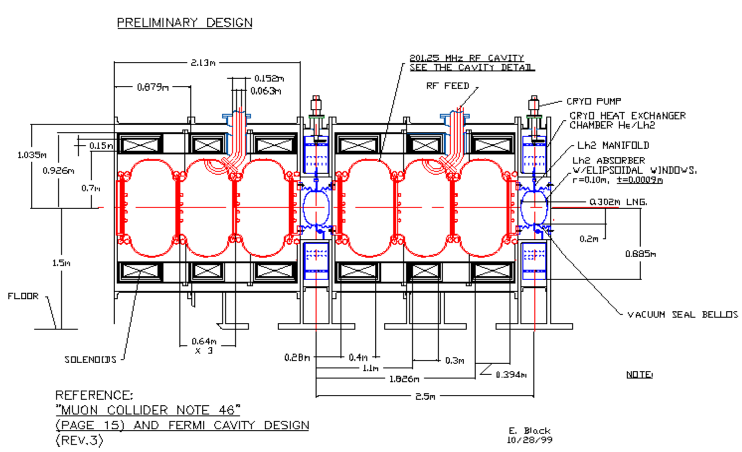

Figure 1: Conceptual layout of two cooling cells, taken as the basis for the design of the rf systems layout of the cooling channel. Changes of the cooling channel design during the study have not been implemented here for two reasons. The first one being that the peak power requirement per meter does not vary significantly for the different designs, and the second one being that we used the full 6 month study time to develop a consistent engineering design.

With the parameters in Table 1 to work with, a number of different rf devices have been investigated. Given the issues of either limited gain, limited experience, or geometric size of the devices, it was decided at this early stage to propose a klystron (even though the length is an issue, possibly as long as 7.75 meters down to maybe less than 4 meters for a Multibeam Klystron). A klystron in many ways seem less risky than other devices and should have a very good lifetime and performance. The MTBF (Mean time between failure) is an important consideration from the very early stage of the design, since there will be about 75 systems operating in the Cooling Channel alone. With no experience in building a pulsed 10 MW peak power klystron with klystron at 200 MHz, development time and significant R&D money is needed to implement such a design.

FREQUENCY:	201 MHZ
Rf Power:	5 MW /m
Rf Pulse width:	150 μsec
Duty Factor:	0.23%
Rep Rate:	15 Hz
Length of Channel:	~150 m

Table 1: Preliminary design parameters for the rf system in the cooling channel.

10.2.1 Proposed RF Station Blocks

The klystron specifications are shown in Table 2. The 10 MW rating is meant to achieve approximately 50% efficiency, but the klystron could most likely run at higher power levels with some reduction in efficiency. The final klystron's peak power requirements will depend on the specific cavity design for the cooling channel, which at this point in time is not finalized.

10.2.1.1 RF Power Source – Multi-Beam Klystrons

Table 2 lists a possible design envelope for a Multi-beam klystron operating at 10 MW. Special attention will be required to keep the cost per klystron to a reasonable level. This will most likely involve trade-offs in the following areas: rf versus mechanical design in the gun region, the output window, the rf cavities, and magnetic focusing. It may be that the total lengths shown in Table 3, for a multi-beam klystron are just not practical because of cavity coupling, geometry, or other mechanical constraints. The multi-beam option, nevertheless, has the potential of reducing the length considerably, which at least would allow the use of existing infrastructure in industry or other laboratories during the R&D phase. It should be mentioned that this technology has been demonstrated to a certain extent (see for example TESLA design report[2]). In the presently foreseen layout, one 10 MW klystron will drive two cavities similar to the ones shown in Figure 1. A total of 75 klystrons station would therefore be required with about one Klystron every 2 meters.

PEAK RF POWER OUTPUT:	10 MEGAWATT
Beam Voltage:	~ 65 Kvolts
Beam Current:	~ 310 amps.
Duty Factor	0.23%
Rep Rate:	15 Hz
Efficiency:	~ 50%
Gain:	~ 50 dB
Rf output connection:	14 inch diameter copper coax with EIA flange.

Table 2: Multi-beam klystron specification

Frequency, MHz	200			
RF Power, MW	10			
μPerveance , $A/V^{1.5}$	2			
Efficiency, %	44			
Item	Value	Value	Value	Units
Type	ring	3 pole	2 ring+1	-
Number of beams	6	12	19	-
Vb	81	62	51	kV
Itotal	279	368	442	A
Bz	233	251	264	G
Total anode dia	53.3	58.4	60.9	cm
l_q	6.201	5.279	4.759	m
Gun + collector len	1.05	0.87	0.77	m
Total length is from	2.6	2.18	1.96	m
to	4.15	3.51	3.15	m

Table 3: Design envelope for a Multi-beam klystron [1].

10.2.1.2 Modulator Specifications for the Proposed Multi-Beam Klystron

The Modulator specifications are given in Table 4. With recent advances in high power solid-state electronics, Insulated Gate Bipolar Transistors (IGBTs) are a very attractive (and cost effective) solution for delivering high voltage to the klystron. Similar modulators with much longer pulse length have been built for the TESLA test facility. Solid State Modulators have been built commercially for similar applications and are being considered for use in other high energy physics projects, currently planned [2]. (The HV power supply is included as part of the Modulator.) Each klystron will have its own Modulator.

VOLTAGE:	65 KVOLTS
Peak Power:	20 Megawatts
Current:	310 Amps
Average Power:	60 Kwatts
Pulse Width:	200 uSec.
Size:	1.2 x 1.2 x 2.4 Meter
Rep Rate:	15 Hz.
Droop:	~ 5%

Table 4: Solid State IGBT Modulator specifications.

10.2.1.3 14 inch Diameter Coaxial Transmission

A 14 inch diameter rigid coaxial transmission line with standard EIA flanges will be used to couple power from the klystron to the cavity. To preserve the coaxial line's interior surface and insulators, the line will be pressurized to 0.5 psig with dry air. There will be two rf windows in each system. The klystron window is an integral part of the klystron. The other window is located at the input to the rf cavity. The total electrical wavelength between the klystron and the cavity will be adjusted to be an integer number of half wavelengths long.

10.2.2 Water Skid – Temperature Regulation

Each water system will supply tempered water for each two meters of cavity. This local water skid will have its own heaters, pumps, de-ionized water loop, and heat exchangers with primary cooling to the heat exchanger supplied from a central chilled water loop. Approximately 22.5 Kwatts of heat will be dissipated in each two meters of cavity. Low conductivity water (LCW) of about 10 MΩ cm resistivity will regulate the temperature of the cavities. The water skids will be located as shown on the floor plan layout. This location was chosen to minimize both the piping to the tunnel and equipment gallery piping.

10.2.3 Station Relay Racks

Each rf station will have five racks for housing controls, power supplies, LLRF (Low Level RF), and a 250 W solid state driver amplifier. These racks are the standard 24 inches wide by 30 inches deep and 86.5 inches high. The different components installed in the rack are listed below.

Controls - Digital I/O & Analog monitor

The control system could be similar to the one used at Fermilab's Main Injector which uses a local VME based system for local station applications and communication with the main control room (ACNET).

Power Supplies

A number of ion pump power supplies will be required for the klystron and the accelerating cavity along with the klystron solenoid power supplies.

LLRF

Each station will have a local feedback loop for phase regulation. Spark detection will include circuits to protect the Klystron, rf windows, cavity surfaces, and transmission line. A commercially available 250 W solid state amplifier will be used to drive the klystron.

10.2.4 Water distribution

The water distribution system is a standard water system for this type of an installation (stainless steel piping). The requirements for the normal conducting cavities in the cooling channel have been included.

	Per station	75 stations
95 degree cooling LCW	75 gpm	5625 gpm
Industrial chilled water	20 gpm	1500 gpm

Table 5: List of requirements for the cooling water requirement.

10.2.5 Electrical Power

The AC power distribution will be done by using cable trenches as shown on the floor plan of the building (comp. Figure 3). Only signal cables will be located in overhead be cable trays.

480 Volt 3-phase		Per station	75 Stations
	Filament:	5 kW	375 kW
	Modulator:	60 kW	4500 kW
	Solenoid power supplies:	10 kW	750 kW
	Solid State rf Amp:	2.5 kW	188 kW
	Water Skid:	20 kW	1500 kW
	Misc:	10 kW	750 kW
	Pumproom:		750 kW
120/208 volts			
	Relay racks:	5 kW	375 kW
	Ion pump PS:	3 kW	225 kW
	Misc:	2 kW	150 kW
Total Power		117.5 kW	9,562.5 Kw

Table 6: Summary of electrical power requirements.

10.2.6 Installation

Since the rf systems will be installed in a new building, all of the supporting utilities for the high power rf will be installed as part of the building construction. The LCW piping, ICW piping, 480/208/120 AC power distribution, and cable trays will be an integral part of the construction. Two overhead cranes running the length of each equipment gallery are required for installation of the klystrons and solenoids. They will mainly be used if a klystron and/or a solenoid has to be replaced. The width of the building can probably be reduced to about 75 feet if the klystron R&D program determines that the fabrication of 200 MHz, 10 MW klystrons with a total length of fewer than 15 feet is feasible. The klystrons could be mounted vertically in this case.

10.2.7 Equipment Gallery Layout for the Cooling Channel

Figure 2 and Figure 3 show a portion of a typical rf gallery layout along with a cross section of the building. The building is approximately 150 meters long by 30 meters wide. Each single rf source can supply enough peak power for 2 meters of rf structure. Therefore, the klystrons are not only arranged side by side, but also on both sides of the gallery. The modulators are next to the klystrons with enough space reserved for maintenance.

10.3 Considerations and Specifications for the Superconducting Accelerator

The three superconducting accelerators consist of the preaccelerator, the first recirculating Linac (RLA1) and the second recirculating Linac (RLA2). With the use of superconducting cavities, the power loss in the cavities is negligible and because the energy extracted by the beam does not have to be replenished during the pulse, a very slow fill mode will be used (compare chapter 7 on the Muon Accelerator Driver). The peak power per unit length in order to charge up the cavities to the operating gradient can therefore be comparatively low. In order to minimize the number of active components, the peak power delivered per klystron station should be maximized. For the required pulse length of 2 milliseconds, a comparison was made to existing klystrons in terms of average rf power being achieved versus peak power. A 10 MW

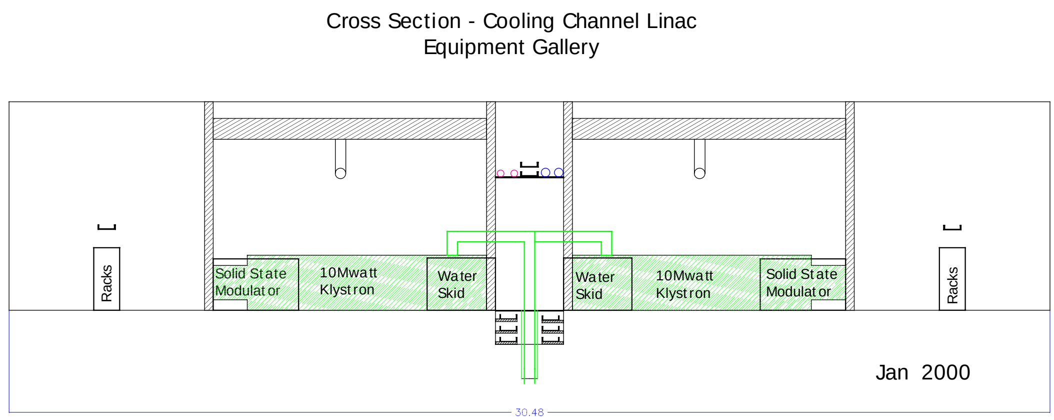

Figure 2: Cross section of equipment gallery

klystrons operating at a pulse length of 2 milliseconds, and a repetition rate of 15 Hz would clearly not be limited in terms of average power as compared to other high power devices. The length of such a klystron is similar to the ones proposed for the cooling channel, but a much larger collector is required because of the larger duty cycle.

10.3.1 Klystron Layouts for 200 and 400 MHz

The klystrons that have been considered for the superconducting accelerators are multi beam klystrons as well, and are very similar to the one described in Table 2 and Table 3. The basic advantage of more beams per klystron is a reduced voltage and therefore a reduced length of the rf circuit. At 400 MHz, the length reduces even more. For the 200 MHz klystron, beam parameters identical to the cooling channel klystron were assumed. For the 400 MHz klystron, the same arguments hold. At this frequency the current density goes up as well as the power dissipation in the collector. From a technical point of view this klystron is more challenging than the 200 MHz klystron.

Frequency, GHz	0.4			
Rf pwr, MW	10			
μPerveance , $A/V^{1.5}$	2			
Efficiency	44%			
Item	Value	Value	Value	Units
Type	ring	3 pole	2 ring+1	-
Number of beams	6	12	19	-
Vb	81	62	51	kV
I total	279	368	442	A
Bz	233	251	264	G
Total anode dia	53.3	58.4	61.0	cm
l_q	3.170	2.692	2.423	m
Gun + collector len	1.05	0.86	0.77	m
Total length is from	1.84	1.54	1.38	m
to	2.63	2.2	2.0	m

Table 7: Preliminary design parameters for a 400 MHz klystron operating at 10 MW output power [1].

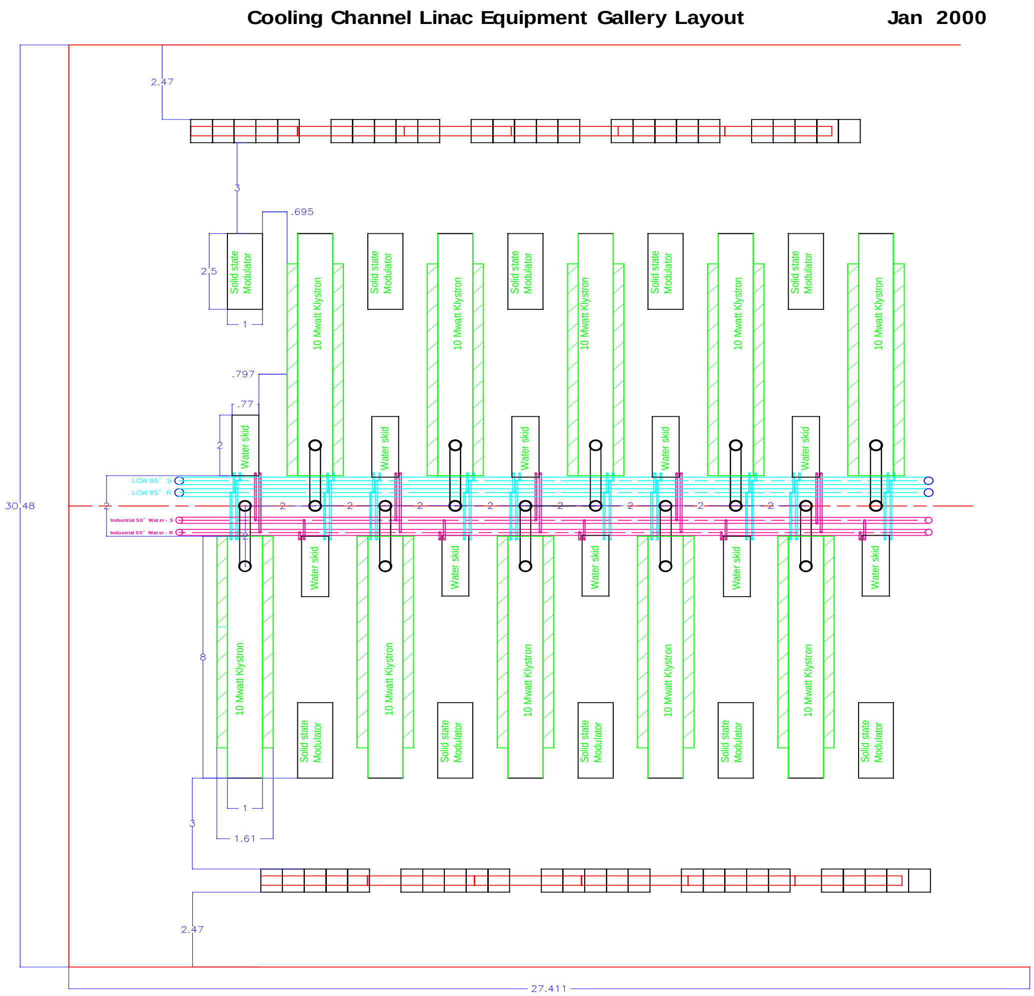

Figure 3: Partial floor plan of equipment gallery for the cooling channel.

10.3.2 Power Distribution into the Cavities

The power distribution into the superconducting cavities is described in this section. The 200 MHz cavities have a peak power of 820 kW/cell which is necessary to fill each cell within 2 msec. For 400 MHz cavities, only 200 kW/cell is required. The rf power distribution into the cells and the total number of klystrons are shown in Table 8. Similar to the Cooling Channel's 75 rf stations, a total of 80 klystrons and modulators are required for the three superconducting accelerators.

Name	Freq MHz	Pulse width msec	MW per Linear meter	Cells per klystron	Number cells	Total installed Votage/GeV
preaccel.	200	2	0.55	10	320	3.6
RLA1	200	2	0.55	10	231	2.6
RLA2	400	2	0.2	60	1,511	8.5
Total						14.7
Name	Peak MW	Ave Pwr kW per klystron	No. of klystrons	Linear meters per klystron	Linear meters	Average rf Power MW
Preaccel.	8.25	247.5	32	15	480	7.9
RLA1	8.25	247.5	23	15	347	5.7
RLA2	9	270	25	45	1133	6.8
Total			80		1960	20.4

Table 8: Description of the power distribution for the superconducting accelerators.

10.4 Conclusion

It became obvious very early in the study that the high power rf systems are one of the major cost drivers for the whole facility. In the cooling channel, the klystron density required to feed the normal conducting cavities represents an additional difficulty which leads to a comparatively large rf power installation with a large klystron gallery and a high density of klystrons. The average rf power required for each accelerator is almost identical for each accelerator and would be four times as high for RLA2, if RLA2 would operate with 200 MHz cavities. Therefore, there is a strong desire to go to 400 MHz at this point in the accelerator chain. The intrinsic efficiency for converting AC to rf power for both rf systems in the cooling channel and in the superconducting accelerators, is assumed to be very high. The long rf pulse length in combination with the use of Multi-beam klystrons will allow higher efficiencies than usually achieved in pulsed rf systems. For this report, a modulator efficiency of 85% will be assumed, which brings the system efficiency to approximately 35% and therefore the total average power consumption for the RLA's for the rf to 60 MW of ac power.

REFERENCES:

[1] courtesy of D. Sprehn, Stanford Linear Accelerator Center. Provided during working meeting on Feb.17th and 18th at Fermilab, Feb.2000, "Feasibility of Super-Conducting RF systems and Magnets for Muon Acceleration".

[2] (editor: R. Brinkmann, et al.) "Conceptual Design Of A 500-Gev E+ E- Linear Collider With Integrated X-Ray Laser Facility. VOL. 1+2", DESY-1997-048, May 1997. 1183pp.