SRF for Muon Colliders*

H. Padamsee,
Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853

Abstract

Interest in the Muon Colliders is growing [1]. Electron-positron colliders beyond 2 TeV CM energy are likely to limited by background from beamstrahlung, and proton colliders beyond 20 TeV CM are likely to be limited by the sheer size of the multi-hundred km circumference. Being 200 times more massive than electrons, muons do not suffer from beamstrahlung limits. A 3 TeV muon collider is likely to fit on a site such as Fermilab. But muons are unstable. Problems from muon decay are the heat load, large detector background and a neutrino radiation hazard. The last adversity can be turned into the fortune of an intense neutrino source.

1 INTRODUCTION

Like electrons and positrons, muons are point particles, so that their energy is not shared among constituents, as in the case of the quark and gluon components of protons. Being 200 times more massive than electrons, the radiative energy loss of muons is less by a factor of 1.6 billion (200 raised to the fourth power). Therefore muons can be accelerated to high energies by recirculation in small arcs. TeV energy muons can be stored and collided in small storage rings. The catch is that muons are unstable, with a rest frame life time of 2.2 microseconds. But the time dilated lifetime at one TeV is 21 milliseconds, long enough for storing 1000 turns in a 6 km circumference ring. The trick is to produce, capture, cool and accelerate the low energy, short lived muons as fast as possible. For rapid acceleration superconducting cavities are ideal.

It is likely that the acceleration will be the most expensive part of the Muon Collider. Fig. 1 reproduces the lay out for a generic muon collider from [2]. We will address mainly the acceleration systems after the muon cooling section. Since development of RF structures is a long lead time item, it would be advisable to address this work early, or at least in parallel with the extremely challenging muon production and muon cooling stages.

2 MUON COLLIDER PARAMETERS

Table 1 reproduces some of the relevant parameters for the first linac and subsequent recirculators[1]. We aim to present scenarios for the use of SRF cavities for all the accelerators listed, and from these scenarios, to draw lessons about where development efforts are necessary. Although the original Table 1 calls for copper cavities in the first linac (0.1 to 0.7 GeV) as well as for the first two recirculators (0.7 to 7 GeV), we will discuss SRF linacs for these columns also.

3 SRF ACCELERATION STAGES

At the high energy end, from 200 to 1500 GeV the concept is to use TESLA type cavities at 1300 MHz, although these cavities may have to be improved with respect to their HOM properties. For the high bunch charge and 10 mm bunch length the beam induced HOM power will be on the order of 200 W/m, demanding very efficient extraction. For our estimates we assume that 10% of this power is dumped in liquid He.

In vertical tests[3], TESLA cavities now routinely reach E_{acc} = 25 - 30 MV/m at Q values above 5×10^9. The success of TESLA cavities at 1300 MHz has lulled the Muon Collider Collaboration to adopt a complacent attitude toward acceleration development, especially when faced with the severe technical challenges of other systems, such as muon cooling and the muon production. However, because of the longer bunch lengths at lower energies, the RF frequency desired decreases to 800 MHz between 50 and 200 GeV, and to a prodigious 200 MHz at lower energies. At the longest bunch length it may even be necessary to go down to 100 MHz, but we hope that this will be only be needed for a very small fraction of the overall acceleration.

Although there is considerable SRF experience at 350 MHz and 500 MHz, there is no experience at all in 200 MHz systems - especially in pulsed operation - and very little experience at 800 MHz. The advent of high intensity proton linacs for neutron sources is likely to fill the 800 MHz gap over the next five years. We will show that the scope of the systems from 200 to 800 MHz is quite significant compared to the 1300 MHz RF, so that it would be wise to address 200 MHz RF development early. Another key point is that a First Muon Collider (FMC) is most likely to be targeted at a maximum energy of 50 GeV, so calling *exclusively* for the low frequency systems. Therefore the fact that TESLA acceleration systems exist at 1300 MHz is likely to be of little help in the birth of the Muon Collider.

In general, the higher the gradient the shorter the linac and the less the muon losses from decay - a major design consideration. The success of 500 MHz KEK-B Nb cavities and 400 MHz LHC Nb/Cu cavities in reaching accelerating gradients of 15 MV/m at 4.2 K encourages us to pick 15 MV/m as the gradient for 100 - 200 MHz systems, 20 MV/m for 800 MHz. and 25 MV/m for

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1300 MHz. At the lower frequency the attraction of Nb/Cu cavities becomes quite strong, especially since the cost of sheet Nb becomes a major component. Further it may be possible to use thicker sheet copper to obtain a lower Lorentz force detuning coefficient for these 200 MHz behemoths.

For Q_0 values, we chose 1x 10^{10} at the operating temperature of 4.5 K for 100 - 200 MHz and the same Q_0 at the operating temperature of 2.1 K for the 800 MHz to 1300 MHz structures. Our estimate is based on a residual resistance of 10 nΩ, plus a BCS resistance given by

$$R_{BCS} = 1.2\text{x}10^{-4} \text{ x } \frac{1}{T} \text{ x } \left(\frac{\text{Freq MHz}}{1500 \text{ MHz}}\right)^2 \text{ x } e^{\left(\frac{-17.67}{T}\right)}$$

Here we take into account any gains in BCS Q that may be obtained by baking at 140 C and reducing the RF surface mean free path [4,5]. For 200 MHz and 4.5 K, the BCS resistance is also about 10 nΩ, resulting in an expected Q of $1.3\text{x}10^{10}$.

Our aim is to calculate the capital cost-intensive items such as, RF power, linac length, refrigerator size as well as the AC power for each of these acceleration stages. We will then insert some very preliminary numbers for the capital costs to determine in which billion dollar class the scope of a 3 TeV collider is likely to fall. Since this is a first cut we neglect reserves needed as for items, such as RF control or refrigeration.

By discussing one system (7 - 50 GeV) in detail we present our strategies, assumptions and algorithms. Assuming the gradient of 15 MV/m, the active length of this linac is 260 m, and the total voltage to be installed in this stage is 3.9 GV, comparable to the LEP-II installation. At 200 MHz the cell length = 0.75 m. The number of cells depends on the coupler power capability and ease of handling large lengths. For both reasons we probably do not wish to exceed two cell units. It should be possible to put several cavity units into one cryostat to improve the filling factor.

RF Power Considerations

To find the size of the RF peak power installation, we start with the average beam power.

$$\text{Average Beam Power} = \text{Bunch charge x bunch frequency x (Final energy - Initial Energy)}$$
$$2\text{x}10^{12} \text{ x } 1.6\text{x}10^{-19} \text{x } (50 - 7)\text{x}10^{9} = 410 \text{ kW}$$

To obtain the peak RF power we need the RF-on duty factor.

$$\text{RF on duty factor} = \text{RF on time x rep rate} = 15 \text{ Hz x } 64\ \mu\text{sec} = 10^{-3}$$

The RF has to stay on for 11 beam recirculation passes through the arcs which are 1.74 km in length. Therefore the RF on time required for the beam on will be

$$\text{RF on time} = \text{Number of recirculations x } \frac{\text{circumference}}{c} = 64\ \mu\text{sec}$$

We neglect the 10 ns time between the two muon bunches. The peak RF power for this stage is then 430 MW, which translates to a peak beam power of 1.65 MW/m, or 1.2 MW per coupler for single cell units. Clearly high power coupler development will be important, especially if we wish to use 2-cell units. Couplers used for HPP in vertical test stands have successfully been operated with one MW and 200 µsec.

Before we can determine the klystron power we need to estimate the total pulse length, which includes the filling time, dominated by the Q_{ext} of the input coupler. Assume that we aim to match to the beam power.

$$Q_{ext} = \frac{\text{Gradient}^2}{\left(\frac{R}{Q}\right) \text{ x Peak Beam Power per meter}} = 8.2\text{x}10^5$$

For R/Q (Ω/m), we scale with frequency from the TESLA structure.

$$\frac{R}{Q}\left(\frac{W}{m}\right) = 1080 \text{ x } \left(\frac{200 \text{ MHz}}{1300 \text{ MHz}}\right)$$

Then

$$\text{RF fill time} = \frac{2 \ln 2 \text{ x } Q_L}{\omega} = 0.9 \text{ ms}$$

Therefore the total RF on time = 0.96 ms. A survey (carried out in '92) of available klystrons showed that the available peak power capability of klystrons decreases with increasing pulse length according to Fig. 2. At 1 ms pulse length we can count on 4 MW klystrons, although the impetus of TESLA has pushed this power capability up by a factor of 2. We will continue to use graph of Fig. 2 to chose the lower klystron power. The total number of klystrons needed is 113.

N = 2×10^{12} Muons per bunch
Rep Rate = 15 Hz
Luminosity = 7×10^{34} cm^{-2} sec^{-1}

Parameters of Acceleration for 3 TeV Collider — TESLA Like

Acc. type		linac	recirc	recirc	recirc	synch	synch	synch
Magnet type			warm	warm	warm	warm	hybrid	hybrid
rf type		Cu	Cu	Cu	SC Nb	SC Nb	SC Nb	SC Nb
E^{init}	(GeV)	0.10	0.70	2	7	50	200	1000
E^{final}	(GeV)	0.70	2	7	50	200	1000	1500
Circ.	(km)	0.07	0.12	0.26	1.74	4.65	11.30	11.36
Turns		2	8	10	11	15	27	17
Loss	(%)	6.11	12.28	10.84	13.94	10.68	10.07	2.65
Decay heat	(W/m)	3.67	15.02	16.89	15.91	19.44	30.97	18.09
B_{pulse}	(T)					2	2	2
B_{fixed}	(T)		0.70	1.20	2		8	8
frac pulsed	%						73	43
Ramp freq.	(kHz)		162	57.34	8.00	2.15	0.50	0.79
Disp.	(m)		0.40	0.60	0.80	1	2	4
βmax	(m)	0.89	3.97	8.75	36.29	52.20	108	120
Mom. compactn	%		1	-0.25	-0.50	-0.50	-0.50	-1
σ_z^{init}	(cm)	16.34	8.53	5.29	3.57	1.59	0.96	0.78
$\Delta p/p^{init}$	(%)	19.27	8.49	5.41	2.47	0.82	0.35	0.09
σ_y	(cm)	0.45	0.45	0.42	0.48	0.22	0.16	0.08
σ_x	(cm)		3.40	3.25	1.98	0.82	0.71	0.36
Pipe full height	(cm)	4.46	4.52	4.22	4.77	2.20	1.62	0.78
Pipe full width	(cm)	4.46	33.95	32.49	19.79	8.20	7.06	3.62
rf Freq	(MHz)	200	100	200	200	800	1300	1300
Acc./turn	(GeV)	0.40	0.17	0.50	4	10	30	30
Acc. time	(μs)		3	8	62	232	1004	631
η	(%)	3.82	0.96	1.97	1.11	10.15	14.37	12.92
Acc. Grad.	(MV/m)	8	8	10	10	15	25	25
Synch. rot's		0.81	0.76	1.02	5.82	19.14	54.29	31.30
Cavity rad.	(cm)	54.88	110	60.47	76.52	19.13	11.77	11.77
rf time	(ms)	0.04	0.12	0.05	0.56	0.40	1.25	0.96
Tot. peak rf	(GW)	0.21	0.14	0.59	1.31	1.06	1.16	1.04
Ave. rf power	(MW)	0.14	0.25	0.45	11.04	6.32	21.91	15.07
rf wall	(MW)	0.64	0.88	1.62	32.47	18.59	44.72	30.76

Table 1: Parameters for a 3 TeV Collider [1]

At Qext = 8.2×10^5, the corresponding bandwidth is 244 Hz. This may be a challenge for pulsed operation in the presence of Lorentz force detuning. On the other hand, as we discussed earlier, the use of thick copper for the Nb/Cu may be an appropriate countermeasure.

Refrigeration

To obtain the dynamic heat load, we first calculate the RF duty factor which depends on the fill time, the flat top and decay time.

RF on duty factor =
Rep rate (RF on time + fill time + decay) =
= 0.019

The 2% duty factor is similar to TESLA. The total RF dissipated power in 4.5 K helium is then

$$\text{Total Dynamic Heat Load} = \frac{\text{Gradient}^2 \text{x Active Length x RF Duty Factor}}{(\frac{R}{Q}) \times Q_0}$$

$$= 685 \text{ W}$$

For the large diameter cryostat that will accompany the 200 MHz cavity we assume a static heat leak of 5 watt/m. Using a filling factor of 0.5, the total static heat leak for this stage will be 2.6 KW, far larger than the dynamic heat load. Clearly, filling factor and static heat load are areas where improvements will be welcome. Another component of the heat load is the fraction of beam induced HOM power that will be dissipated in liquid helium. For the HOM loss factor (k||) we scale from TESLA with frequency and bunch length (equals 1 mm for TESLA and 36 mm for this stage.).

$$k_{||} = 6.6\text{x}10^{12} \text{ x } \left(\frac{200 \text{ MHz}}{1300 \text{ MHz}}\right)^2 \text{ x } \sqrt{\frac{1\text{x}10^{-3}}{36 \text{ x}10^{-3}}}$$
$$= 2.6 \text{ x } 10^{10} \text{ Volts/Coulomb}$$

$$\text{Total HOM Power} = k_{||} \text{ x Length x (Bunch Charge)}^2 \text{ x Bunch Frequency x Number of Recirculations} = 230 \text{ W}$$

HOM power couplers have to be designed to extract 90% of this power, which is well within the range of present HOM coupler technology. Allowing for an average distribution system heat load of 0.5 W/m, the total cryogenic heat load is therefore

Total Cryo Heat Load =
685 (dynamic) + 2600 (static) + 23 (HOM fraction) + 265 (distribution) =
3573W

Capital and Operating Cost Estimates

With economies of scale and cost dependence on frequency we estimate that the unit cost for the cryomodules will be given by

$$\text{Cryomodule Cost per meter} = 133\text{x}10^3 \text{ x } [0.8]^{\text{Log (L)}} \text{ x } \sqrt{\frac{1300 \text{ MHz}}{\text{Frequency (MHz)}}}$$

For L = 260 m of 200 MHz structures, the result is of the order of 200 k$/m. The capital cost for the refrigerator is about 1300 $/watt at 4.5 K. For higher energy stages that operate at 2 K we have increased the capital cost coefficient by a factor of 2.

A 1992 survey of klystron peak power cost showed that the cost increases with pulse length as shown in Fig.3. For 1 ms pulse we anticipate a unit cost of 0.06$/peak watt. To this we add the cost of the High Voltage power supply and modulator for each klystron at 0.5 M$, resulting in a unit RF cost of 0.73 M$ per klystron system. In summary, the capital cost distribution for 7-50 GeV acceleration stage turns out as:

Table 2

Linac	51 M$
RF	82 M$
Refrigerator	4.3 M$
Total Capital	138 M$

Note that the RF cost dominates.

With a klystron efficiency of 0.65 and an overall refrigerator efficiency of $3\text{x}10^{-3}$, the total AC power is 9.6 MW. The beam power to AC wall power efficiency is a not too impressive 4%. This is because of the small number (11) of recirculations for this stage. For the higher energy stages the efficiency rises.

Table 3 shows the results of comparable calculations carried out for the other acceleration stages. The algorithms have been adjusted to take care of different RF frequencies and different operating temperatures. Note that the efficiency rises to 20% at the top energy.

Table 3:

Energy Span (GeV)	RF Frequency (MHz)	Active Length (m)	Peak RF Power (MW)	Heat Load (W)	Capital Cost M$	AC Power (MW)	Efficiency (%)
Linacs							
0.4 - 0.6	100	13	72	211	18	1.4	0.14
0.6-1.0	200	27	72	325	15	0.76	0.5
Recirc. Linacs							
1-2	100	8	195	103	20	1.2	0.8
2-7	200	33	365	382	30	1.3	3.6
*7-50	200	260	430	3575	138	10	3.8
50-200	800	500	412	4168	105	7.2	20
200-1000	1300	1185	1223	31900	310	37	21
1000-1500	1300	1175	500	23640	220	27	18
Totals		3200	3269	64. kW	856	86	
Neutrino Factory							
0.6-1	200	27	163	311	20	1	0.23
1- 10	200	150	915	1600	109	5.8	0.94
10-50	200	666	1148	8285	267	26	0.92
Totals		842	2226	10.2 kW	396	33	

4 MUON STORAGE RING FOR NEUTRINOS

The path to a 3 TeV muon collider is filled with many challenges. A time scale shorter than 20 years seems unlikely. Recall that the TESLA effort was started around 1987, and is still many years towards completion. As a first step, the collaboration is very interested in building a Muon Storage Ring based neutrino source. Atmospheric neutrino, solar neutrino and short baseline accelerator experiments accumulate evidence to show that neutrinos have a small but finite mass. If this is confirmed, it could be a big part of the solution to the "dark matter" problem: "Where is 90% of the mass of the universe?" If neutrinos have mass, then according to the theory they should oscillate in flavor, which opens up exciting fields of neutrino flavor physics, such as the search for CP violation in neutrino interactions.

The goal of the neutrino factory would be to provide 3 x 10^{20} muon decays per year. The demands on muon cooling are much reduced over that for a collider. One scenario[6] calls for three acceleration stages: 1 GeV linac followed, by two recirculators. Only four recirculation loops are envisioned, which results in a rather low efficiency. The last part of Table 3 shows the capital cost items.

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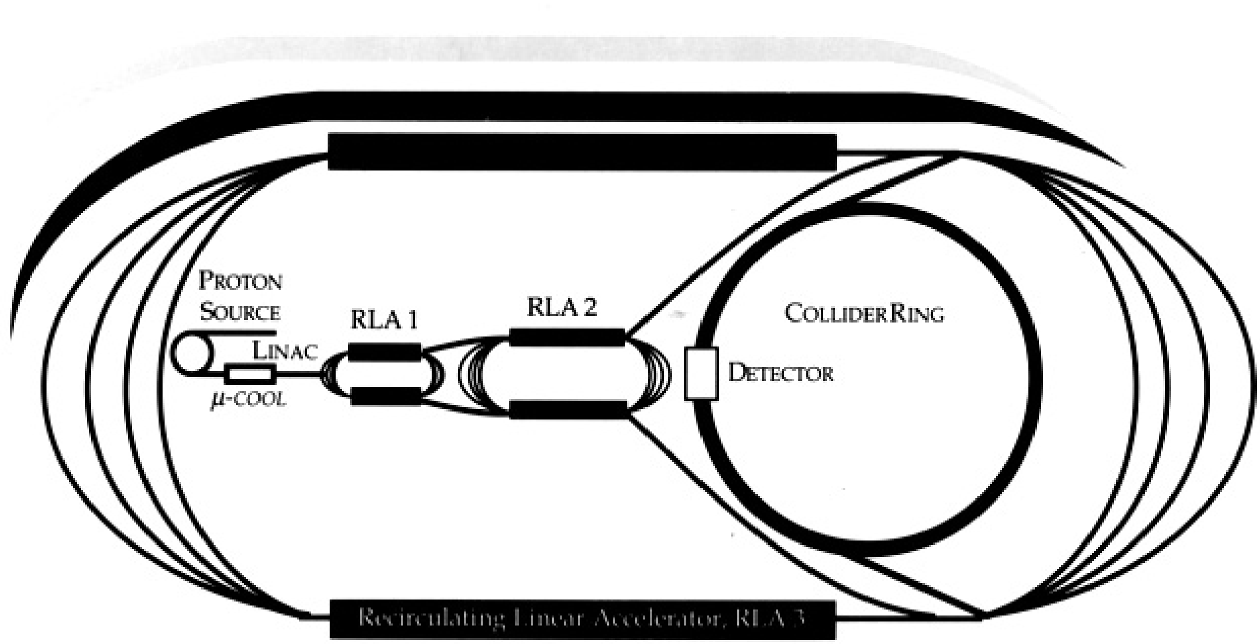

Fig. 1: Generic Layout for a 3 TeV collider [2].

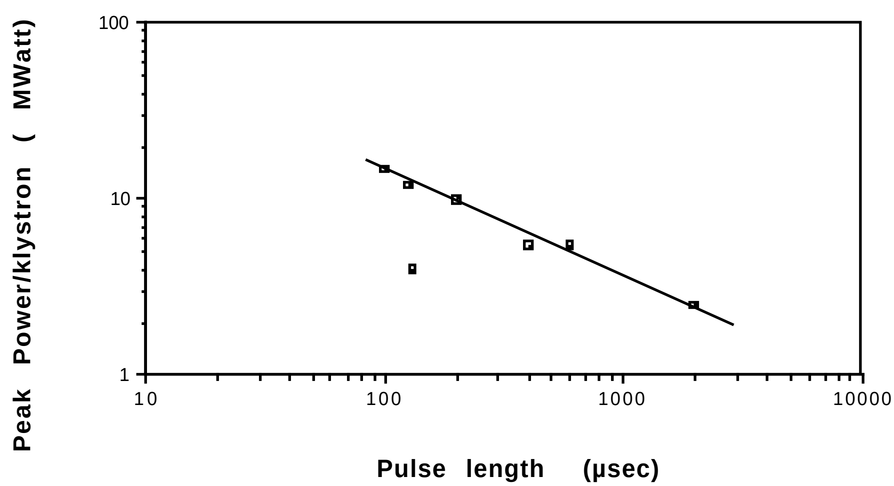

Fig. 2: Peak power of klystrons vs. pulse length.

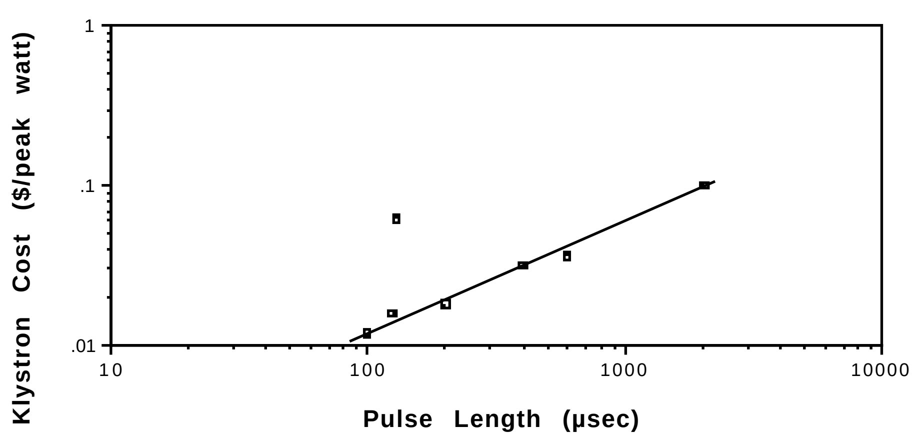

Fig. 3: Unit cost of klystron peak power vs. pulse length.