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A MAD (Muon Accelerator Driver) Concept for a Neutrino Factory

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Preface

This is a legacy work in progress technical note written as a part of ongoing work on the muon driver accelerator for the Fermilab Neutrino Factory. It is presented not as a conclusive design document but rather as a portion of the paper trail leading to JLAB-TN-00-009, “Design of a Muon Accelerator Driver for a Neutrino Factory”, by J. Delayen, D. Douglas, L. Harwood, G. Krafft, V. Lebedev, Ch. Leemann and L. Merminga. Many of the issues presented below are appropriately addressed in the later note.

Abstract

Following an interaction amongst Fermilab Neutrino Factory study group members and staff from the Jefferson Lab Beam Physics and Instrumentation Department an informal working group met and discussed issues associated with the design of a Muon Accelerator Driver (MAD) for a neutrino factory [1]. Though not necessarily representative of the views of all working group members (and perhaps not even technically correct in all details!), this note draws freely on the content of these and subsequent informal discussions and presents a “straw-man” proposal for a muon accelerator driver concept.

Baseline Parameters

Baseline Muon Accelerator Driver (MAD) parameters have been provided by Fermilab [2] and are presented in Table 1.

Table 1: Baseline MAD Parameters

Parameter	**Baseline Value**
$p_{injection}$	190 MeV
E_{final}	50 GeV
$\varepsilon_N^{injected}$	1.5 mm-rad
$\varepsilon_N^{extracted}$	3.2 mm-rad
$\Delta E/E_{final}$	± 2%
σ_l^{bunch}, injected	12 cm
$\sigma_{\delta p/p}^{bunch}$, injected	11%
pulse (macrobunch) length	150 nsec
N_{bunch}/pulse	30
N_μ/pulse, extracted	3×10^{12}
f_{pulse}	15 Hz

Table 2 presents a list of parameters derived from the baseline set that will be useful in subsequent discussion.

Table 2: Derived MAD Parameters

Parameter	**Derived Value**	**Comments**
I_{ave}	7.5 µA	Macroscopic average current
$I_{in\ pulse}$	3 A	Current in macropulse
P_{ave}	350 kW	Macroscopic average beam power
$P_{in\ pulse}$	150 GW	Beam power in macropulse
$\beta_{injection}=v/c$	0.87	
$\varepsilon_{injected}^{geometric}=\varepsilon_N/\beta\gamma$	9×10^{-4}	Injected geometric emittance
$\varepsilon_{extracted}^{geometric}=\varepsilon_N/\beta\gamma$	6.4×10^{-6}	Extracted geometric emittance
$\sigma_{betatron}^{injected}(\beta=1\ m)$	3 cm	Injected rms spot size at beam envelope of 1 m
$\sigma_{betatron}^{extracted}(\beta=1\ m)$	2.5 mm	Extracted rms spot size at beam envelope of 1 m

We note that the source phase space is extremely large, leading to large spot sizes at injection and throughout the system. This implies a need for large apertures and acceptances globally. Though the average beam current and power are modest (7 µA/350 kW) the current (3 A) and power (150 GW) in the macropulse are impressive, suggesting transient and collective-effect driven phenomena may be important and/or performance limiting. The relatively low injection velocity (b=0.87) implies a need for multiple cavity types to accommodate potential beam/RF phase slip during acceleration.

Issues and Constraints

The primary MAD issue is muon preservation – the system must manage decay and losses during acceleration and provide a useable phase space to the neutrino factory storage ring. Secondary issues are collective effects, transport/acceleration of a very large phase space, and cost/performance optimization. The latter drives consideration of recirculation; this in turn imposes a constraint through the minimum recirculatable energy (due to RF phase slip from pass to pass and large geometric phase space volume at low energy). Thus, muon accelerator concepts should allow for a very large acceptance post-injection preaccelerator before any recirculation is attempted. Jefferson Lab experience with the CEBAF Front End Test Recirculation Experiment [3] and the IR FEL Demo Project [4] suggests that a γ of 10 to 20 is adequate to allow good recirculation performance. Though a more quantitative analysis is possible (in which the performance of various injection/reinjection energy choices are examined [5] in the following we will use a 2 GeV preaccelerator output energy (γ=20) as a sufficient and appropriately conservative working choice.

Muon Survival – Decay of muons over a nominal 1.5 µsec rest frame lifetime imposes a need for rapid acceleration to high energies. Fractional muon survival rates are readily computed both analytically and numerically [6] as a function of average gradient during acceleration to 50 GeV. Figure 1 illustrates survival rate as a function of average real-estate gradient; Figure 1a shows survival for acceleration from 0 to 2 GeV, as in a pre-accelerator; Figure 1b shows survival for acceleration from 0 to 50 GeV. Average gradients of 5 MV/m will allow survival of over 80% of injected muons; this represents an average radiation power load of ~1 W/m over the accelerator length. These are operationally acceptable numbers that will figure into the choice of accelerator technology. We remark that the loss rate is not ~20% of the average final beam power of 350 kW because muon decay is distributed along the linac and low energy muons (representing a smaller fractional power load) are lost at a higher rate.

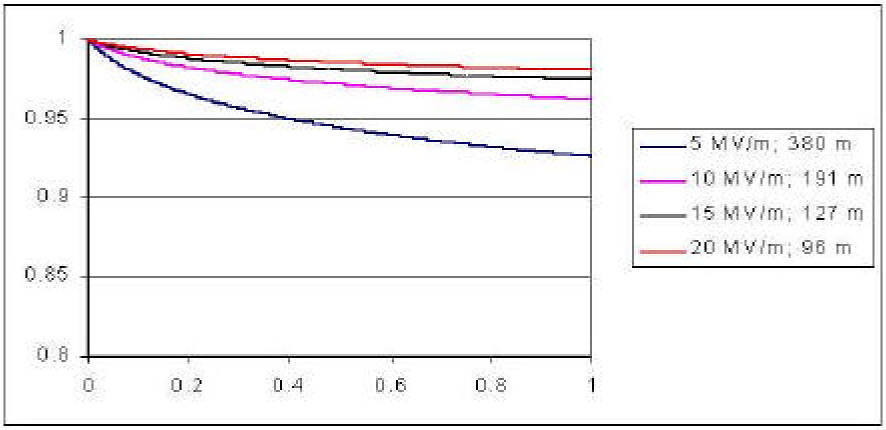


Figure 1a: Muon Survival for 0 to 2 GeV as a function of real-estate gradient and distance along machine.

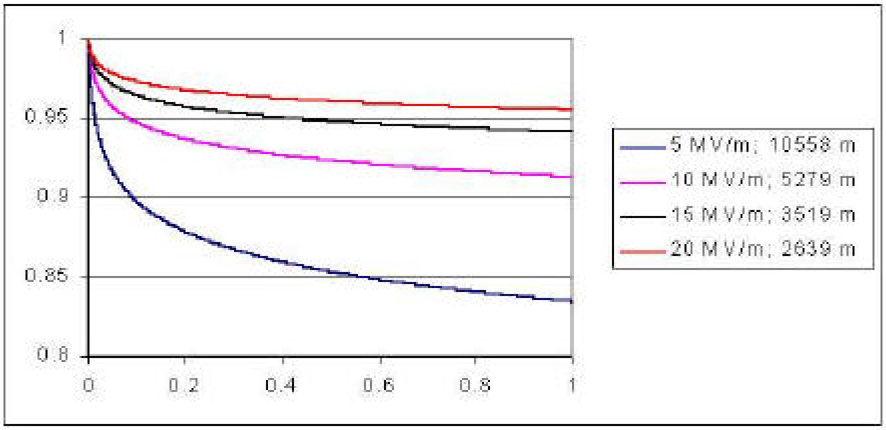


Figure 1b: Muon Survival for 0 to 50 GeV as a function of real-estate gradient and distance along machine.

Collective Effects – For a given accelerator concept, the design team must ascertain the impact of the acceleration of a relatively high (3 A) average current during the macropulse. At this level, transient and collective effect driven phenomena will be important. Of particular interest to recirculated designs are BBU and other HOM and wake-driven instabilities.

Acceleration and Transport of Large Phase Space – Even with muon cooling, the phase space at injection is both transversely and longitudinally large. With strong focussing – average beam envelopes of 1 m – the rms transverse spot size at injection will be of order 3 cm. Large apertures will therefore be required. Similarly, the longitudinal phase space, with an rms energy spread of ~10 MeV and rms bunch length of 12 cm, will require a large longitudinal acceptance accelerator. Even with adiabatic damping, downstream beam transport will require large betatron and momentum acceptance. Linac technology choices and implementations will have to acknowledge this constraint.

Technology Choices

The acceleration technology used in the driver must meet four requirements:

1) Frequency must be consistent with source micropulse repetition rate and provide longitudinal acceptance adequate to capture essentially “all” of the injected muons
2) Gradient must be high enough to ensure adequate muon survival
3) RF power must be transferred from wall plug to beam in a cost effective manner.
4) Transverse acceptance must be adequate to avoid significant muon loss.

The source presently provides a 12 cm (rms) long bunch at a 200 MHz micropulse repetition rate. The preaccelerator/accelerator must therefore operate on a harmonic of this fundamental. We note that a full 4σ bunch subtends (at an injection β=0.87) 140° of 200 MHz RF, with a full momentum spread of ~40%. Management of this phase space will require selection of one of the following choices:

1) further muon cooling before acceleration,
2) management of a further degraded phase space after acceleration atop a nonlinear waveform,
3) use of harmonic cavities, or
4) reduction of the micropulse repetition rate to more manageble levels, such as 100 MHz, with associated longer RF wavelengths.

Choices 1 and 2 are inconsistent with muon preservation; choice 3 will nominally impose aperture restrictions inconsistent with the large injected emittances and required transverse acceptance. The iris aperture and frequency of a cavity scales linearly with one another. CEBAF 5-cell cavities 1.5 GHz have a 7 cm aperture, so 200 MHz cavities will have an aperture of 52.5 cm; a 600 MHz third harmonic cavity will have an aperture of only 17.5 cm. This is inadequate for the injected beam, which has a 3 cm rms spot size at locations with a beam envelope function of 1 m (and thus is ~10 cm when the beam envelope is 10 m). Third harmonic cavities will therefore introduce severe aperture constraints if a 200 MHz fundamental is chosen.

This leaves choice 4. We note that this is consistent with all basic issues and requirements, assisting greatly by improving both capture efficiency/longitudinal acceptance and transverse aperture. We also note that by the above scaling the third harmonic, 300 MHz, will use cavities with ~35 cm aperture. This can in principle provide adequate aperture (almost 4σ at a beam envelope of 10 m) and thus retains the possibility of using a third harmonic system to improve longitudinal acceptance. We present in Table 3 revised base and derived parameter sets using this micropulse repetition rate. These data will be used in the following discussion.

Table 3: Revised Parameter Set At 100 MHz.

Table 3a: Baseline MAD Parameters

Parameter	**Baseline Value**
$p_{injection}$	190 MeV
E_{final}	50 GeV
$\varepsilon_N^{injected}$	1.5 mm-rad
$\varepsilon_N^{extracted}$	3.2 mm-rad
$\Delta E/E_{final}$	± 2%
σ_l^{bunch}, injected	12 cm
$\sigma_{\delta p/p}^{bunch}$, injected	11%
pulse (macrobunch) length	300 nsec
N_{bunch}/pulse	30
N_μ/pulse, extracted	3×10^{12}
f_{pulse}	15 Hz

Table 3b: Derived MAD Parameters at 100 MHz

Parameter	**Derived Value**	**Comments**
I_{ave}	7.5 μA	Macroscopic average current
$I_{in\ pulse}$	1.5 A	Current in macropulse
P_{ave}	350 kW	Macroscopic average beam power
$P_{in\ pulse}$	75 GW	Beam power in macropulse
$\beta_{injection}=v/c$	0.87	
$\varepsilon_{injected}^{geometric}=\varepsilon_N/\beta\gamma$	8×10^{-4} m-rad	Injected geometric emittance
$\varepsilon_{extracted}^{geometric}=\varepsilon_N/\beta\gamma$	6.8×10^{-6} m-rad	Extracted geometric emittance
$\sigma_{betatron}^{injected}(\beta=1\ m)$	3 cm	Injected rms spot size at beam envelope of 1 m
$\sigma_{betatron}^{extracted}(\beta=1\ m)$	2.5 mm	Extracted rms spot size at beam envelope of 1 m

Technologies available for the preaccelerator and accelerator include pulsed or CW copper and pulsed or CW SRF, with or without recirculation. CW copper is gradient limited (leading to large muon losses) and will have enormous RF losses in this application. It is therefore not a candidate technology.

The preaccelerator cannot, as noted above, be recirculated. RF power demands will not allow the use of pulsed copper with recirculation in the main accelerator(s). Room temperature RF simply cannot sustain the required RF gradient and power for the extended time periods associated with recirculation (several tens of microseconds for beams in the energy range of interest). The following are therefore the candidate technologies for the preaccelerator and accelerator: Preaccelerator: Pulsed copper, CW SRF, Pulsed SRF, without recirculation; Accelerator: Pulsed copper without recirculation, Pulsed or CW SRF with or without recirculation.

Available gradients in each technology are given in Table 4. All are adequate to ensure muon survival for neutrino factory storage ring injection. We now examine each driver accelerator system separately to select the appropriate candidate technology.

Table 4: Available Gradients at 100 MHz

Technology	Real Estate Gradient (MV/m)	Comments
Pulsed Cu	12	Kilpatrick limit at ~100 MHz [7]
CW SRF	7.5	15 MV/m with 50% packing fraction
Pulsed SRF	Maybe 10	Enhancement by pulsing

Preaccelerator – Consider first the use of pulsed copper technology. The peak RF power required in the preaccelerator will, for pulsed copper operation, be ~3 GW (2 GeV x 1.5 A) over a 300 nsec macropulse. This will require 30 100 MW klystrons and an energy compression system like SLED. The RF drive system therefore probably costs well over 50 M$ and will be operationally complex.

In contrast, an SRF based system can be rather simple. Benson and Delayen [8] and subsequently Harwood and Delayen [9] have noted that the stored energy in a 100 MHz SRF cavity is very large, and that it consequently can be used to accelerate a macropulse without significant gradient droop. Note [10] that the Q, stored energy E_s, frequency f and power loss P over a single period of an oscillator are related by the following expression.

$$Q = 2pf\,\frac{E_s}{P}$$

For a CEBAF 5-cell cavity at 5 MV/m, Q~10^{10}, f=1.5 GHz, and P~1 W, so that E_s =1 J. The stored energy in a cavity will scale as f^3 (with volume) and g^2, the square of the gradient (as the square of the stored fields). Thus, at 100 MHz and 10 MV/m (roughly the requirment to get a real-estate gradient of ~5 MV/m) the stored energy will be $(15)^3$ x $(10/5)^2$ x 1 J = 13.5 kJ. Continuing the assumption of a direct volumetric scaling of a CEBAF cavity, the 100 MHz cavity would have an active length of ~7.5 m, giving 75 MeV energy gain. The resulting RF power in the 1.5 A macropulse would therefore be 75 MV x 1.5 A = 112.5 MW, with an energy transfer in the 300 nsec macropulse of 112.5 MW x 300 nsec = 33.75 J. The power at the end of the macropulse thus sags to ~13466.25 J, a fall off to 99.75%. The gradient will droop by the square root of the power, or to 0.99875%, which for a large momentum spread beam of the type under consideration is negligible. We note that several macropulses could be sent through the cavity without significant impact; this observation will figure into the discussion of recirculation, below, in the context of the main accelerator..

SRF thus provides a viable candidate technology for the preaccelerator. We note that the cavities in the above example transfer only an average power of 75 MV x 7 μA= 525 W. A cost effective scenario would therefore be to “slowly” fill the cavities – over a few milliseconds – with low peak power klystrons or tetrodes at a 15 Hz repetition rate. Beam could then be accelerated in each using the energy stored between macropulses, whereafter a slow refill could occur.

Choice of an SRF linac, either pulsed or CW, is thus consistent with all design goals. It is also possibly a cost optimum when compared to copper. As noted above, a copper RF drive system alone would cost in excess of 50 M$; this cost will, by contrast, provide ~20 installed upgraded (7-cell) Jefferson Lab cryomodules providing 1.6 GeV of energy gain. Although the 100 MHz cavity technology must be quite different from the CEBAF implementation to be cost effective (surface cooled lead-sputtered copper [11] may be an appropriate concept), this comparison shows SRF to be at least potentially cost competitive with room temperature technologies. Coupled to the relative operational ease associated with SRF as compared to pulse-compressed copper, the choice of an SRF linac is clear.

We will therefore use in the following discussions of a machine concept a 100 MHz “pulsed” (slow fill, accelerate using stored energy) SRF linac preaccelerator. The issue of actual CW or pulsed SRF operation remains to be resolved; some advantage in gradient and cryogenic load through TESLA-mode pulsed operation may be achieved in this application as well.

Two obvious problems with this technology are quench protection and SRF heat load. The former represents a novel challenge – if a quench initiates, 13500 J of stored energy must be safely extracted before mechanically damaging the cavities. SRF heat load is a more mundane, though similarly challenging, problem. As noted above, $Q\sim 2pf\, E_s/P$; using a stored energy of 13.5 kW and a 100 MHz frequency while assuming the CEBAF cavity Q of 10^{10} can be maintained suggests P ~ 850 W for 75 MV of acceleration! Given that 2 GeV is needed (27 such cavities), the full heat load from the preaccelerator will be 23 kW, or some 70 times the CEBAF load. The cryogenic operating point (4 K or 2K), and the associated refrigeration efficiency, will thus be a significant design choice for this machine.

Accelerator – As noted above, the technologies available are pulsed copper without recirculation and pulsed or CW SRF with or without recirculation. The content of the technology selection process is here essentially the same as it was in the preaccelerator. A few points are however illuminating. A pulsed conventional linac will require 75 GW power in the macropulse to accelerate the beam (1.5 A x 50 GeV). This is quiet impressive, but even this pales in comparison to resistive wall losses.

Recalling the above discussion of stored energy in a 100 MHz SRF cavity, we note that to some level the stored energy in a cavity of a particular frequency does not depend on the details of the cavity construction. There is simply some volume of field providing gradient to a beam. Thus, any old 100 MHz cavity at 10 MV/m will have, when filled, the 14 kJ stored energy estimated above. Recalling that copper has a Kilpatrick limit of ~12 MV/m at 100 MHz (Table 4) and that the stored energy goes as the square of the gradient, we see that the conventional cavity will have a stored energy of ~20 kJ. Now apply the relation $Q\sim 2pf\, E_s/P$ with an assumed Q of 10^4 to get P~1.25 GW. This cavity will supply an energy gain of e x 12 MV/m x 7.5 m or 90 MeV to the beam. The main accelerator will therefore need 50 GeV/90 MeV = 556 such cavities – for a total resistive wall loss power load of 700 GW in the macropulse. Use of conventional accelerator technology will therefore require production of Terawatt levels of RF power, albeit for only short (μsec) time intervals. If one conservatively estimates that pulsed RF power costs are ~10 k$/MW (peak power) (for example, assume a 100 MW SLAC S-band klystron costs 1 M$), the required 775 GW peak power RF drive system will cost on the order of 7.75 G$. This is probably unacceptable.

We constrast this with the pre-accelerator SRF scenario detailed above. SRF technology provides a viable source of stored RF energy that can be used to accelerate the macropulse without achieving relatively enormous peak powers. Consider the system described above – a 100 MHz SRF linac providing locally 10 MV/m (real estate average of 5 MV/m) over a number of

7.5 m long cavites. Each cavity has a stored energy of 14 kJ and provides 75 MeV energy gain to the beam. The 1.5 A macropulse therefore pulls 112.5 MW for 300 nsec, or 33.75 J, from the cavity. The full accelerator needs 50 GeV/75 MeV = 667 such cavities; they deliver 22500 J of energy over 300 nsec, or 75 GW, to the macropulse (just at in the copper system). However, as noted above, this energy can be replenished “slowly” between macropulses – for the 15 Hz repetition rate, a fill of as long as 66 msec can be used. This would be essentially CW operation of the SRF system; and would require an RF power source providing 22500J/66 msec = 340 kW.

Using the same “conservative” (though, in this case, admittedly unfair and inaccurate) RF cost as was applied to the copper system, we guesstimate an RF drive system cost of 0.34 MW/ x (10 k$/MW)= 3.4 k$. This, of course, is nonsensically low. A more accurate estimate might be supplied by noting the Jefferson Lab IR FEL Upgrade allows 1 M$ for 200 kW of CW RF power, and replacing all 338 few-kW klystrons in CEBAF would cost several million dollars. The key observation is not the precise system cost but rather that it is several orders of magnitude lower for SRF than for copper. The precise costing details will depend on the operation mode – pulsed or CW of the SRF system. This in turn will depend on a detailed analysis of the advantages of either; as noted in the discussion of the preaccelerator, there may be cost and performance advantages to pulsed SRF operation in terms of both gradient and cryogenic load.

This highlights another different between conventional and SRF technologies – an SRF system requires refrigeration. We note that $Q \sim 2pf\ E_s/P$ provides, for the parameters at hand, a dynamic heat load P of ~ 850 W per cavity at a Q of 10^{10}. Using again the 667 cavity number for 50 GeV, we find the total linac heat load to be ~600 kW. If 2^o K operation is desired (costing ~4000$/W), a ~2.4 G$ refrigerator will be needed; if 4^o K operation is used (at a lower cost of 1600$/W) the refrigerator will be “only” 1 G$ [12]. Two conclusions are obvious – first, a careful consideration of operating temperature is needed, and secondly, SRF is potentially less costly than room temperature technologies, even with cryogenic systems taken into consideration.

As noted in the discussion of the preaccelerator, the 34 J cavity to beam energy transfer during the macropulse induces only a small gradient sag. Consequently, SRF systems can support recirculation as a cost optimization measure. The detailed cost/performance optimum must observe the details of the system concept – for example, the fact that the phase space is of very poor quality and that any recirculator must have extremely large acceptance – but cost trends can be determined from very simple arguments and cost estimates.

A cost optimization through the use of recirulation requires knowledge of approximate linac, transport and civil construction costs. The linac costs derive from SRF, RF power, and refrigerator costs; the transport costs typically include vacuum, magnets, diagnostics, and other beamline components. Civil costs cover tunnel and ancillary service buildings.

In the following, we draw on CEBAF/Jefferson Lab experience to develop a costing expression. CEBAF construction SRF costs were roughly 1 M$ for 20 MeV of installed acceleration; Jefferson Lab upgrade costs project providing 80 MeV installed acceleration for ~3 M$. We assume 100 MHz SRF will provide lower gradient at escalated cost, and thus use a working figure of 6 M$ for 40 MeV, or an RF cost C_{RF}=150 k$/MeV. We note that this does not include refrigeration, which, as seen above, may be significant. The following discussion therefore underestimates linac cost and will therefore tend to predict a reduced optimum number of passes.

Transport costs for CEBAF were ~30 M$ for ~4 km of beam line (the total beam path is 6.5 km, but 2.5 km is in the linacs and is multipass), or roughly 7.5 k$/m. This should be compared to SSC costs, which (assuming ~half the machine cost was in transport) provided 60 km of machine for ~6 G$, or 100 k$/m. We therefore will use an intermediate value of C_T=50 k$/m. We note that this does not allow for “nonlinearities” in transport costs, such as the nonlinear cost increase with number of passes due to rising complexity in systems used to separate beams of differing energy for recirculation or to recombine them for further acceleration. The following description will therefore be valid only for “a few” passes – transport systems in “many” (5? 10? 20?) pass machines will not cost scale linearly because of rapidly increasing complexity

Civil engineering (tunnel) costs at CEBAF were ~50 M$ overall, but included construction costs other than those of the ~1.5 km tunnel (end stations, service and office buildings, etc). We therefore adopt a civil cost C_C=25 k$/m.

<u>Preaccelerator</u>: The preaccelerator cost may be estimated as follows.

$$C = \Delta E C_{RF} + L(C_T + C_C)$$

For the preaccelerator, $L=DE/G$, with G the available real-estate gradient. The cost can then be expressed as follows.

$$C = \Delta E C_{RF}\left(1 + \frac{(C_T + C_C)}{C_{RF} G}\right)$$

Using G=5 MV/m and costs as above the civil/transport term is numerically only 0.1 – indicating that RF costs dominate the preaccelerator. Evaluating this expression, we find a total cost of C=330 M$.

For a recirculating accelerator the cost expression depends on the number of passes N, the length L_T of a single recirculation arc, the linac length L_L, and DE, the total energy gain (E_{final}-$E_{injection}$), as follows.

$$C = \frac{\Delta E C_{RF}}{N} + L_L(C_T + C_C) + 2L_T(C_T + C_C)$$

As above, L_L=DE/G. The transport system arc length is somewhat murkier; one might guess that ~1/2 the arc will devoted to matching, spreading, and recombining beams, the other half to actual recirculation. If momentum compaction management is needed, the arc dipole packing fraction may be of order 50% (or less, but, what the heck!), so that the full recirculation length will be ~ 2 (only half is arc) x 2 (only half is dipole) x π x ρ_{Efinal}. The final bend radius is, in turn, $B\rho_{Efinal}/B_{peak}$, so that the cost can be expressed as follows.

$$C = \Delta E\left\{\frac{C_{RF}}{N} + \frac{(C_T + C_C)}{NG} + \frac{8p(Br)_0}{B_{peak}}\left(1 + \frac{E_{injection}}{\Delta E}\right)(NC_T + C_C)\right\}$$

Here, $(B\rho)_0$ is the 33.3564 kg-m/(GeV/c) constant. The optimum number of passes gives ∂C/∂N=0. This in turn suggests

$$\frac{\partial C}{\partial N} = 0 = \Delta E\left\{-\frac{C_{RF}}{N^2} - \frac{(C_T + C_C)}{N^2 G} + \frac{8p(Br)_0}{B_{peak}}\left(1 + \frac{E_{injection}}{\Delta E}\right)C_T\right\}$$

or

$$N = \sqrt{\frac{C_{RF} + (C_T + C_C)/G}{\frac{8p(Br)_0}{B_{peak}}\left(1 + \frac{E_{injection}}{\Delta E}\right)C_T}}$$

Typically, DE>>$E_{injection}$, so to a fair approximation, this expression is independent of injection and extraction energy and depends only on relative system costs. For the costs above, for conventional technology (B_{peak} ~ 12 kG) this expression suggests N=7; for superconducting technology (B_{peak} ~ 60 kG) this would suggest N=15. As noted above, these numbers are probably “low” from the perspective that installed RF costs will include refrigeration as well (some of which, of course, would have to go to superconducting magnets in that case), tending to drive up the optimum number of passes.

We recall, however, the linear scaling of cost with path number assumes the transport system cost scales only linearly with pass number. This is in fact incorrect. As the pass number increases beyond a certain point, the complexity of the transport system, its sensitivity to errors, and difficulties in commissioning and operation drive the system costs nonlinearly. The “floor to ceiling steel” of the CEBAF spreader-recombiners are an example of such system complexity. The above result is simply an indication that transport costs are small in comparison to linac costs, so that the “optimum” is to install as many passes as seems technically prudent. We note as well that the transport system cost is a “small denominator” in this computation – the result will therefore be extremely sensitive to errors in this number.

Experience with CEBAF and various other recirculating and energy recovering machines suggests that high pass number and high injection to final energy ratio introduces operational and performance difficulties [13]. In the system at hand, the injected to extracted energy ratio is 25 to 1; we therefore consider an “accelerator chain” with injection at 2 GeV with acceleration to 10 GeV, with a second machine with injection at 10 GeV with acceleration to 50 GeV. Each machine would have 4 passes with a 5 to 1 injected to final energy ratio. This separation is also advantageous in that it [14] 1) allows the use of a smaller footprint machine initially, bringing muons to 10 GeV with higher average real estate gradient and therefore with less decay, and 2) the first recirculator arcs can be used with variable momentum compactions to optimize the longitudinal match from pass to pass. This process is not unlike the energy compression during energy recovery demonstrated in the Jefferson Lab IR FEL Demo [15], and, comfortingly, will have to occur at momentum spreads not unlike those encountered in the Jefferson Lab machine. We now turn our attention to a more detailed discussion of this concept.

MAD Concept

Based on the above discussion, we propose a MAD concept as shown in Figure 2. It comprises a 2 GeV preccelerator, a 10 GeV recirculator used for initial acceleration/damping/compression, and a 50 GeV recirculator used for primary acceleration. Details of each subsystem are given below.

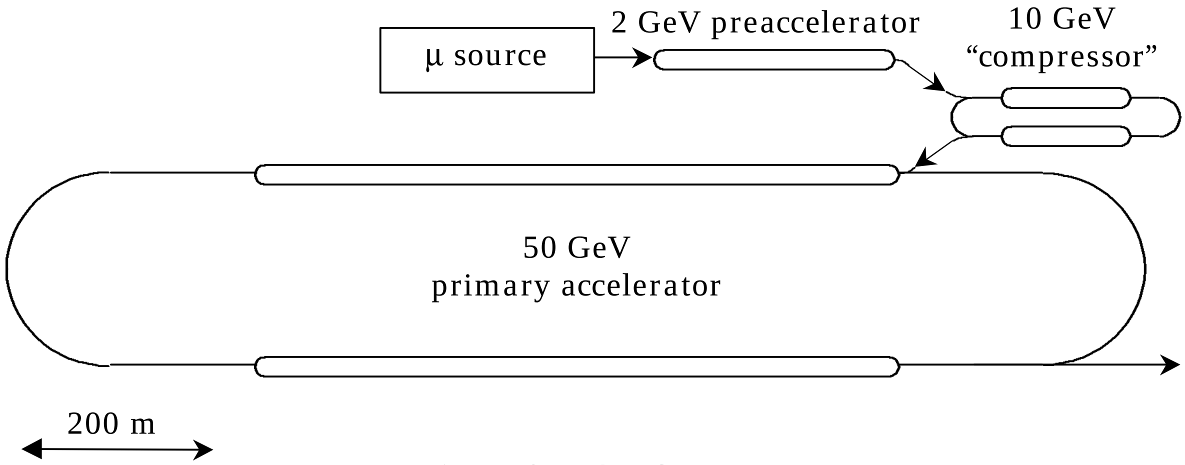
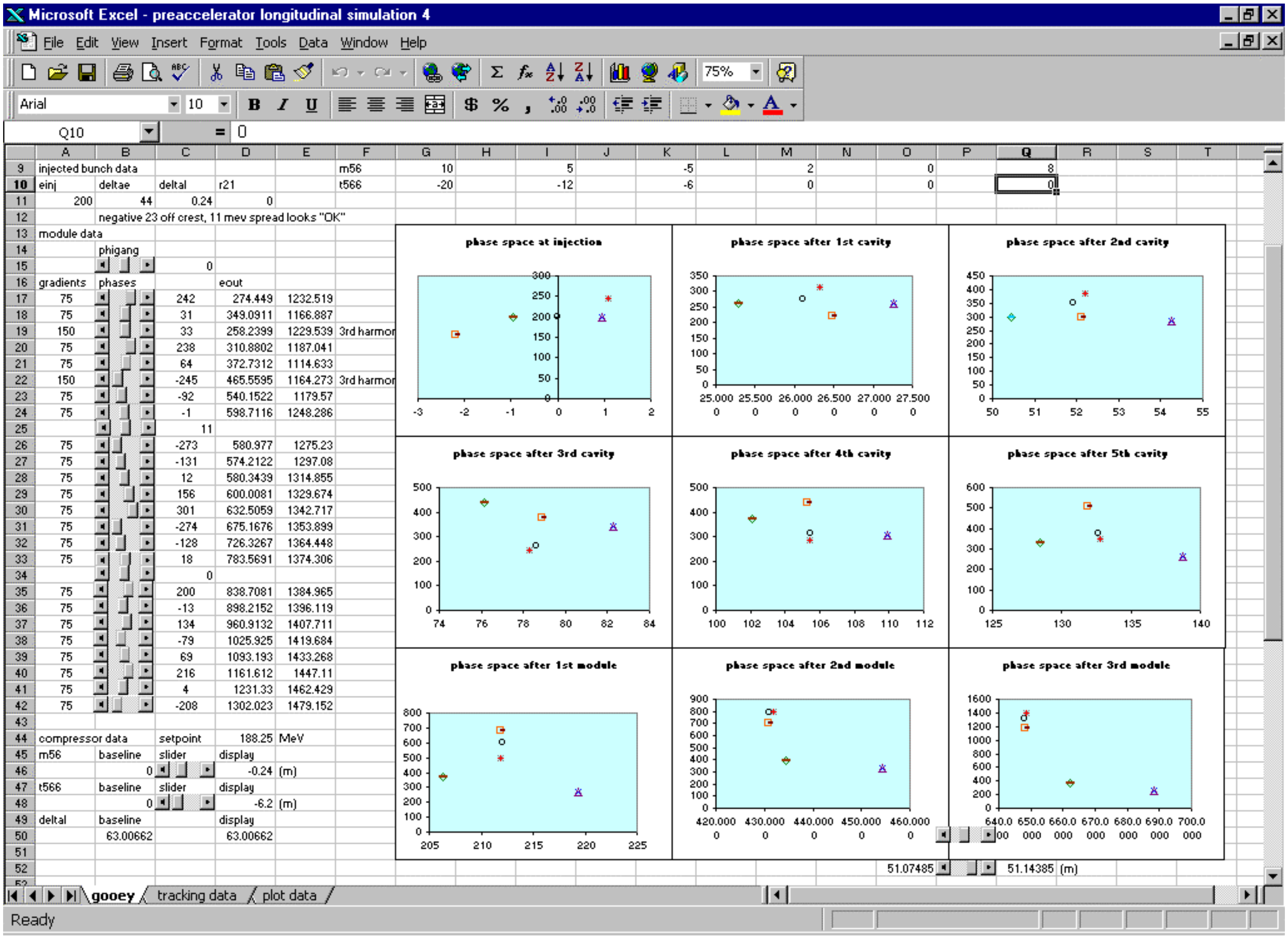


Figure 2: MAD Concept

Preaccelerator - The available source parameters require acceleration and appropriate phase space control prior to recirculation. As discussed above, Jefferson Lab experience suggests that 2 GeV (γ=20) will provide adequate muon velocity to allow recirculation, though this must be quantitatively verified and the design choice subjected to optimization. We assume a Table 4 “real estate gradient” of 7.5 MV/m to ensure adequate muon survival. Various technical issues must be resolved with this system. These include:

1) *Longitudinal phase space management during the acceleration process* – At present, this appears quite challenging [16]. It will likely require use of a combination of single cell and graded beta cavities at no higher than 100 MHz interleaved with magnetic bunch compressors and third harmonic cavities for the correction of RF waveform curvature. A sample output from a simulation of the acceleration process is given in Figure 3 [17]. Evolution of RF waveform curvature driven degradation is evident.



Q10 = 0

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
9	injected bunch data					m56	10		5		-5		2		0		8
10	einj	deltae	deltal	r21		t566	-20		-12		-6		0		0		0
11	200	44	0.24	0													
12		negative 23 off crest, 11 mev spread looks "OK"															
13	module data																
14		phigang															
15			0														
16	gradients	phases		eout													
17	75		242	274.449	1232.519												
18	75		31	349.0911	1166.887												
19	150		33	258.2399	1229.539	3rd harmor											
20	75		238	310.8802	1187.041												
21	75		64	372.7312	1114.633												
22	150		-245	465.5595	1164.273	3rd harmor											
23	75		-92	540.1522	1179.57												
24	75		-1	598.7116	1248.286												
25			11														
26	75		-273	580.977	1275.23												
27	75		-131	574.2122	1297.08												
28	75		12	580.3439	1314.855												
29	75		156	600.0081	1329.674												
30	75		301	632.5059	1342.717												
31	75		-274	675.1676	1353.899												
32	75		-128	726.3267	1364.448												
33	75		18	783.5691	1374.306												
34			0														
35	75		200	838.7081	1384.965												
36	75		-13	898.2152	1396.119												
37	75		134	960.9132	1407.711												
38	75		-79	1025.925	1419.684												
39	75		69	1093.193	1433.268												
40	75		216	1161.612	1447.11												
41	75		4	1231.33	1462.429												
42	75		-208	1302.023	1479.152												
43																	
44	compressor data		setpoint	188.25	MeV												
45	m56	baseline	slider	display													
46		0		-0.24	(m)												
47	t566	baseline	slider	display													
48		0		-6.2	(m)												
49	deltal	baseline		display													
50		63.00662		63.00662													
51																	
52															51.07485		51.14385 (m)

Figure 3: Sample results from simulation of longitudinal transport. Evolution of large momentum spread due to RF waveform curvature is evident.

2) *Transverse dynamics during acceleration* – in addition to managing the longitudinal phase space, the beam must remain focussed and confined. Details of the beam optics solution must allow for transport and focussing of a very large momentum spread beam. This must be done in the presence of RF as well as external focussing from both magnetic lenses (solenoids and/or quadrupoles) as well as that imposed by any required magnetic bunch length compression systems. Defining the details of this system therefore will require the existence of a longitudinal solution (to understand both RF focussing and bunch compressor structure) and some knowledge of the details of the RF structures to be utilized. In addition, external focussing must be applied so as to provide sufficient packing

fraction for the accelerating fields to provide the desired real estate gradient of 5 MV/m. This has implications on the use of focussing outside vs. inside of the cryogenic enviroment required for SRF cavities. The resolution of this issue is made even more involved by the large apertures required.

3) *Acceleration scenario* – given a longitudinal solution, an optimized RF operation scenario must be developed. Specifically, the use of pulsed vs. CW SRF must be evaluated and an appropriate solution developed. The optimum is not immediately clear – pulsed SRF requires less refrigeration but higher RF peak power, CW SRF will require more refrigeration but lower RF peak power. The “best” solution will depend (as in the optimization of pass number!) on the details of individual system costs.
4) *Instabilities and collective effects* – the high average currents required during the macropulse suggest that instabilities, collective and/or wakefield effects may be problematic. Once the details of phase space management are understood, effort should be made to evaluate the implications of the acceleration of such high peak current in an SRF environment.

A 7.5 MV/m real estate gradient value implies ~270 m of linac will be needed for 2 GeV output energy.

<u>Compressor Recirculator</u> – Following the preaccelerator, a first recirculator is used to accelerate the beam from 2 to 10 GeV and to perform longitudinal manipulations to reduce both bunch length and momentum spread. The injected beam will have, at best, a 0.5 m full bunch length and ~80 MeV (4%) full energy spread. Adiabatic damping and bunch length compression may reduce this to ~0.2 m and 2% (200 MeV) at 10 GeV. The machine will again have to be 100 MHz to manage the initial bunch length, but the compression during acceleration (as well as the reduced phase slip) may avoid the need for third harmonic acceleration, at least in the subsequent primary accelerator. The preceding discussion of pass number suggests that it is not possible to quantitatively cost-optimize the design at present. We therefore choose 4 passes as a likely candidate solution; robust 5 pass operation has been demonstrated with CEBAF; we choose a somewhat less challenging 4 pass number so as to accommodate the much larger momentum spread in this device. The machine will thus utilize 2 1 GeV linacs; we assume a nominal real estate gradient of 7.5 MV/m over the linac portions of the system.

Various technical issues must be addressed. These include, as with the preaccelerator,

1) *Details of the longitudinal manipulations* – such issues have been addressed independently by S. Berg [18] and G. Krafft [19]. Of particular

interest are the establishment of the sequence of M_{56} and T_{566} values and acceleration phases required to compress both bunch length and relative momentum spread, and an evaluation of the need for third harmonic cavities in the compressor.
2) *Beam transport system design* – Given a longitudinal solution, a beam transport system solution supplying the requisite compactions, dispersion management, and transverse focussing must be developed. This solution must provide large phase space acceptance (transverse as well as longitudinal) and should adhere to good operability practices.
3) *RF Operation Scenario* – pulsed or CW?
4) *Instabilities* – in addition to the use of high current beams in an SRF enviroment, we now must add in potential for multipass effects.

The assumed 7.5 MV/m real estate gradient suggests two linacs of ~135 m length will be required. Recirculator dimensions are somewhat less clear. As discussed in preceding cost arguments, the recirculator beamline lengths will be about twice the length of the arc proper; this will in turn be set by bend radius and packing fraction. The radius of a 10 GeV beam in a 60 kg field (superconducting dipoles assumed) will be ~5 m. This machine is to provide opportunity for longitudinal manipulations – so we assume a low (25%) packing fraction, for a mean radius of ~20 m and approximate length of 60 m. Allowing another 60 m (for spreader/recombiners) the compressor layout will appear as in Figure 4.

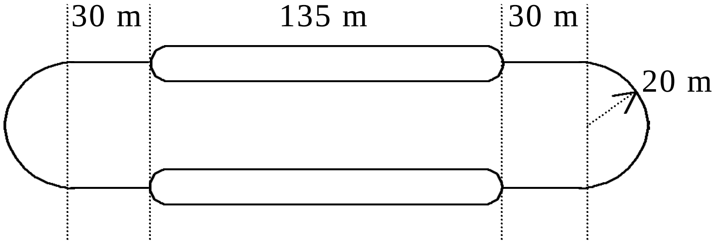


Figure 4: Compressor layout.

The Figure 2 MAD concept allows for bending between preaccelerator and compressor to initiate the longitudinal gymnastics. Detailed design work will be required to specify the precise configuration, but we note a transport of below 135 m length will keep the overall real estate gradient for the preaccelerator above 5 MV/m – adequate for muon survival. We note that this issue may be important in the compressor as well. The total single pass path length is ~510 m, while the active linac length is 270 m. The net real estate gradient is therefore only (270/510) x 7.5 MV/m = 4 MV/m, a bit lower than desirable, though perhaps acceptable at these energies in excess of 2 GeV.

Primary Recirculator – After the compressor, the primary accelerator is used to bring the beam from 10 to 50 GeV. At injection, the beam is assumed to have ~2% momentum spread and 0.2 m length, by virtue of longitudinal gymnastics in the compressor. This might allow the use of a higher frequency system (such as 200 MHz). We note, however, that the injected bunch length subtends about 50° degrees at 200 MHz (just as it subtended ~70° at 100 MHz during injection into the preaccelerator with a length of ~0.5 m). This can, as in the preaccelerator, result in difficulty in acceleration and consequential use of third harmonic cavities. Such a transition should thus not be undertaken without careful quantitative evaluation. We therefore will assume in the following discussion that the primary accelerator remains at 100 MHz.

Given the injected phase space and acceleration cycle, it is likely that the final target full energy spread (Table 1) of 2% can be met. Further reduction of bunch length may be possible as well, provided appropriate longitudinal gymnastics are provided in the recirculator. As with the compressor, there is not at present sufficient detail available to meaningfully optimize the number of passes. We therefore follow the same reasoning as in the compressor, and select a four pass design as a working scheme.

The machine thus comprises two 5 GeV linacs; as in the previous discussions, we assume a nominal real-estate gradient of 7.5 MV/m over these portions of the system. The dimensions of the system scale directly with energy (a factor of 5) from those of the compressor. The linacs will be ~670 m in length. Under the assumption that the beam handling utilizes superconducting magnets the recirculator transport will be ~100 m in mean radius and will require ~150 m for beam separation and recombination prior to recirculation. The real-estate gradient number will be 4 MV/m, as in the compressor; this is probably (marginally?) adequate to ensure muon survival. A machine footprint is given in Figure 5.

Technical issues remain similar to those in both the preaccelerator and the driver. In addition, a feasibility analysis on the use of higher frequency must be performed. An enumeration follows.

1) *Details of the longitudinal manipulations* – an analysis of the need for further bunch compression must be performed. This will tie to the choice of frequency. We note that use of 200 MHz, if possible, may provide higher gradients and lower cryogenic loads, significantly reducing costs.
2) *Beam transport system design* – Given the longitudinal solution, a beam transport system solution supplying the requisite compactions, dispersion management, and transverse focussing must be developed. This solution

must provide large phase space acceptance (transverse as well as longitudinal) and should adhere to good operability practices.

3) *RF Operation Scenario* – pulsed or CW?
4) *Instabilities* – in addition to the use of high current beams in an SRF enviroment, we must again allow for multipass effects.

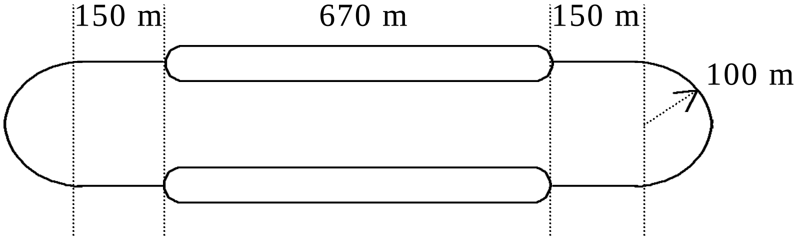


Figure 5: Primary accelerator layout.

MAD Costs

Table 5: MAD Cost Summary

System	Unit Cost	Installed		System Cost	Total Cost
RF	0.15 M$/MV	Preaccelerator	2 GeV	300 M$	
		Compressor	2 GeV	300 M$	
		Primary accelerator	10 GeV	1500 M$	2100 M$
Transport	50 k$/m	Preaccelerator	270 m	14 M$	
		Compressor	2235 m	112 M$	
		Primary accelerator	11164 m	558 M$	684 M$
Civil	25 k$/m	Preaccelerator	270 m	7 M$	
		Compressor	516 m	13 M$	
		Primary accelerator	2568 m	64 M$	84 M$
Cryogenics	1.6 k$/W @ 4^oK 4 k$/W @ 2^oK	160 kW			256 M$ @ 4^oK 640 M$ @ 2^oK
				TOTAL	3124 @ 4^oK 3508 @ 2^oK

Based on the above discussion, we propose a MAD concept as shown in Figure 2. Table 5 summarizes total installed subsystem parameters, unit costs, and total costs. The machine total cost lies in the 3 to 3.5 G$ range, depending on the cryogenic operating temperature.

Issues

A number of issues have been identified by the above discussion. Amongst them are the following.

1) The design needs to address computation of the preaccelerator transverse optics, including RF focussing. It must also provide preaccelerator optics for the large required momentum acceptance (~40% in the front end).
2) There is a need for careful modeling of the longitudinal transport. This should determine how the large momentum spread gets managed before/during recirculation (it may, *e.g.* use the first recirculating linac as a longitudinal manager to get bunch length down, *etc*)
3) The design must provide a concept for large-acceptance optics for both recirculating machines.
4) Overall, a complete optics design is necessary. The low energy means the RF cavities focus a lot, but may provide “free” bunching as well. We must establish if external focussing is needed, and, if so, if is it superconducting and/or in the cryostat. In the latter case, technical problems with large aperture magnets (stray fields) become an issue, but SRF/room temperature transitions eat up a lot of space and thus lower the real-estate average gradient and adversely affect muon survival.
5) The design should provide a detailed computation of minimum recirculatable energy by executing an injection/reinjection energy performance analysis (see, *e.g.*, reference [5]).
6) Estimates of effects of collective effects should be performed.
7) The design must execute a cost optimization of the recirculation process – number of accelerators, number of linacs/accelerator, number of passes, type of recirculation (horizontal, vertical separation, *etc.*)
8) The system will require construction of high Q, high gradient, low frequency SRF cavities (sputtered superconductor-surface cooled copper, for example?). Immediate issues are:
    a) Operating temp
    b) Refrigeration efficiency and cost
9) Quench protection – how to extract large stored energy?
10) Cryo load reduction/gradient enhancement through use of pulsed SRF?

Acknowledgments

This work draws on information arising from various interactions amongst Fermilab and Jefferson Lab personnel. The author does not wish to impugn the reputation of any contributor by associating their names with his shallow understanding of the issues presented in this note. However, the concepts herein did not originate with the author, but rather were drawn from two meetings and various informal discussions. The first meeting was in September 1999 and included members of the Fermilab Neutrino Factory study group (D. Finley and N. Holtkamp) as well as folks from the JLab Beam Physics and Instrumentation Department; the second meeting was in October 1999 with attendees as in Reference [1]. Subsequent coffee-pot analysis was performed with attendees of both meetings and with J. Benesch, C. Bohn (FNAL), J. Preble, and M. Tiefenback. I would also like to thank S.

Berg of BNL for a useful discussion on the accelerator architecture, which supported the decision to use two recirculating linacs in the acceleration process. The author thanks all who particpated and apologizes to any participant whose name may have been inadvertently omitted.

Notes and References

[1] An informal discussion on design issues for neutrino factory muon accelerator driver was held in October 1999. The attendees included S. Benson, J. Delayen, D. Douglas, Ch. Leemann, G. Krafft, L. Harwood, C. Hovater, A. Hutton, L. Merminga, C. Reece and C. Rode. Subsequent discussions included J. Benesch, V. Lebedev, G. Neil, J. Preble, and M. Tiefenback. The Fermilab point of contact for these discusssions was C. Bohn.

[2] C. Bohn, e-mail of 27 September 1999.

[3] N. Sereno, "Experimental Studies of Multipass Beam Breakup and Energy Recovery Using the CEBAF Injector Linac", Ph.D thesis, U. Illinois, 1994.

[4] C. L. Bohn, "Performance of the Accelerator Driver of Jefferson Laboratory's Free-Electron Laser", Proc. 1999 I.E.E.E. Part. Accel. Conf., March 1999, N.Y.

[5] See, for example, D. Douglas, "Lattice Design Principles for a Recirculated, High Energy, SRF Electron Accelerator", Proceedings of the 1993 I.E.E.E. Particle Accelerator Conference, Washington, D.C., May 1993.

[6] Ch. Leemann has provided an analytic calculation; D. Douglas has provided a numerical computation, which was used to generate the graphs in this note.

[7] See, for example, J. LeDuff, "High Field Electron Linacs", in Volume 1 of the Proceedings of the 5th Advanced Accelerator Physics Course of the CERN Accelerator School; CERN 95-06, 22 November 1995.

[8] S. Benson, private communication.

[9] L. Harwood, private communication.

[10] Thanks to J. Benesch for instructing me on this topic.

[11] J. Benesch, private communication.

[12] Costs from C. Rode, private communication.

[13] D. Douglas, “Lattice Design Principles for a Recirculated, High Energy, SRF Electron Accelerator”, *op. cit.*

[14] S. Berg, private communication.

[15] D. Douglas, “Modeling of Longitudinal Phase Space Dynamics in Energy-Recovering FEL Drivers”, JLAB-TN-99-002, 14 January 1999.

[16] L. Harwood, private communication on work in progress.

[17] D. Douglas, work in progress.

[18] S. Berg, private communication.

[19] G. A. Krafft, “Non-Isochronous Recirculation at CEBAF”, CEBAF-TN-92-005, 23 January 1992.