I. ACCELERATION

A. Introduction

Following cooling and initial bunch compression, the beams must be rapidly accelerated. The acceleration needed for a Higgs collider is probably the most conventional part of the machine, and severe problems are not expected in its design, but far less work has gone into its study than into the other elements. No lattices have yet been designed and little simulation has been undertaken.

A sequence of linacs would work, but would be expensive. Some form of circulating acceleration is preferred. At the lowest energies ($<$ 700 MeV) the momentum spread and beam sizes are so large that only a linac is possible. At intermediate energies (to $\approx$ 200 GeV) the acceleration time is so short that any form of magnet ramping is impractical. The conservative option here is to use a sequence of recirculating accelerators (similar to that used at TJNL), but Fixed Frequency Alternating Gradient (FFAG) accelerators are also being studied [1,2] (see next section). At higher energies, the acceleration rate is slow enough that fast rise time pulsed magnets are possible (see below).

B. Acceleration for Higgs Collider

Tb. I gives an early example of a sequences of accelerators for a 100 GeV Higgs Factory, i.e. a machine with the very low momentum spread (0.003 %) and relatively large *rms* transverse emittance ($\approx$ 300π mm mrad).

Following initial linacs, recirculating accelerators are used. The number of arcs in each recirculating accelerator is about 10. In this example, conventional 2 T magnets are used. The effective ramp frequencies that would be needed if pulsed magnets were used are given in the table. The frequencies of 280, 80, and 8 kHz are all assumed too high.

Designs [3] have been made of multiple aperture superconducting magnets (see Fig. 7.12 in [4]) for use in this or higher energy machines. Their use would reduce the diameter of the recirculating accelerator ring and lower particle loss from decay and could be more economical.

Significant work [2,5] has also been done on Fixed Field Alternating Gradient (FFAG) lattices that could replace the multiple arcs (see next section).

In this example, all the accelerating cavities are room temperature copper structures, and the accelerating gradients are modest ($<$ 10 MeV/m). Nevertheless, the acceleration is rapid enough that the total losses from decay are only 30 %. The heating from these decays is also modest ($\approx$ 10 W/m) because of the small number of turns and relatively low energy. Since no superconducting magnets or rf are used in this example, this heating should cause no problem.

1. Design Challenges

The first design challenge arises because of the large transverse emittances (*rms*) ($\approx$ 300 π mm mrad). Strong focusing is required in the lattices. This will result naturally in relatively small dispersions, as are required to contain the relatively large momentum spreads (up to 1.37 % *rms*).

The second challenge is the high instantaneous rf peak powers required, and the resulting large numbers of power sources. For the linacs and early recirculating accelerators, the powers are high because of the high gradients, and low frequencies required to accelerate the long bunches. At these frequencies (200-400 MHz), currently available sources (triodes and tetrodes) have relatively low maximum output powers and are expensive. Low temperature operation of the cavities, and superconducting or conventional SLED [6] systems would reduce the peak power requirements, are being considered.

It should be noted that in the first two recirculators (up to 7 GeV) there is no hope for the rf to keep up with the beam loading. Conventional continuous (cw) matching of the sources to the loaded cavities is not possible. The cavity is filled in a suitable filling time (twice the time constant in these examples), and the rf voltage allowed to sag as the beam makes its multiple passes. If excessive sensitivity to beam current is to be avoided, then the stored energy must be large compared to that used, which is somewhat inefficient.

In the final recirculating accelerator, continuous filling (cw) is just possible, but requires yet higher peak power ($\approx$ 5 GW total at 800 MHz) because of the high acceleration rate. The use of superconducting cavities can reduce losses, and thus reduce this peak rf power source requirement (see next section), but is not used in this example. At this frequency (800 MHz), klystrons are available with greater power ($\approx$ 20 MW) than that of the sources at the lower frequencies, but a yet high power klystron (50-100 MW) could probably be developed.

TABLE I. Accelerator parameters for a Higgs Factory (100 GeV)

Acc. type		linac	linac	recirc	recirc	recirc	sums
Magnet type				warm	warm	warm	
rf type		Cu	Cu	Cu	Cu	Cu	
E_{init}	(GeV)	0.10	0.20	0.70	2	7	
E_{final}	(GeV)	0.20	0.70	2	7	50	
Circ.	(km)	0.04	0.07	0.07	0.19	1.74	2.11
Turns		1	1	8	10	11	
Loss	(%)	2.31	3.98	7.27	7.91	13.94	31.06
Decay heat	W/m	0.89	1.98	11.04	12.99	12.44	
B_{fixed}	(T)			2	2	2	
(ramp freq)	(kHz)			281	79.83	8.00	
Disp	m			1	1.50	3	
βmax	m	0.83	1.42	3.00	5.31	21.08	
σ_z^{init}	(cm)	2.71	2.22	1.42	1.64	0.90	
$\Delta p/p^{\text{init}}$	(%)	3.58	2.80	1.64	0.56	0.32	
σ_y	cm	1.09	1.14	1.01	0.85	0.94	
σ_y	cm			1.93	1.19	1.34	
Pipe full height	cm	10.92	11.42	10.14	8.49	9.39	
Pipe full width	cm	10.92	11.42	19.28	11.94	13.35	
rf freq.	(MHz)	200	200	200	200	400	
lambda/sig 1		55.30	67.49	106	91.46	83.77	
Acc/turn	(GeV)	0.20	0.40	0.17	0.50	4	
Acc time	(μs)			1	6	62	
η	(%)	5.15	5.36	6.36	2.84	6.92	
Acc. Grad.	(MV/m)	8	8	8	10	10	
Synch. rot's		0.62	0.63	0.62	3.92	23.16	
Cavity rad.	(cm)	54.37	54.88	54.88	60.47	38.26	
Beam time	msec	0.00	0.00	0.00	0.01	0.06	
rf time	msec	0.17	0.17	0.17	0.18	0.13	
Tot. peak rf	(GW)	0.05	0.10	0.05	0.26	4.71	5.17
Ave. rf power	MW	0.14	0.24	0.13	0.68	9.54	10.73
rf wall	MW	0.64	1.16	0.46	2.42	28.06	32.75

C. Acceleration for High Luminosity 100 GeV

Table II gives a sequences of accelerators for a high luminosity 100 GeV collider. In this example, superconducting cavities are used the for 7-50 GeV rings. This is given as an illustration, and is not related to the higher luminosity parameters. The reason for the use of these cavities is to reduce the peak power requirement. As noted above, the power is high because the acceleration must be rapid to avoid decay losses, and thus the acceleration rate is also high.

1. Design Challenge

The six dimensional emittance in this machine is the same as in the Higgs collider, but the transverse emittance is smaller ($\approx 90\pi$ mm mradrms), and the longitudinal emittance larger; i.e. the product of the bunch length and momentum spread is larger (by about a factor of 4). If the momentum spread is to be kept low then the very long resulting bunches require lower frequency rf, which is large and expensive. Alternatively one must have lattices with very large momentum acceptances. The latter approach is used in the example given below (Tb. II), with a momentum spread in the first recirculating accelerator of nearly 6 % rms; or about 50 % full width. This is large by conventional standards, but far less than that in the FFAG lattice being studied [2]. Indeed, if a true FFAG lattices were to be used for their convenience of avoiding the switch yards and multi-aperture magnets, then the specified momentum spread would certainly not be a problem.

It would be desirable to use the same accelerator for both modes: Higgs low energy spread, and 100 GeV high luminosity. With little modification, the accelerators described here (Tb. II) would be able to do this, but it is recognized that these parameters are harder to meet than those given in Tb. I.

TABLE II. Accelerator parameters for a High Luminosity 100 GeV Collider

Acc. type		linac	linac	recirc	recirc	recirc	sums
Magnet type				warm	warm	warm	
rf type		Cu	Cu	Cu	Cu	SC Nb	
E_{init}	(GeV)	0.10	0.20	0.70	2	7	
E_{final}	(GeV)	0.20	0.70	2	7	50	
Circ.	(km)	0.04	0.07	0.07	0.19	1.74	2.11
Turns		1	1	8	10	11	
Loss	(%)	2.31	3.98	7.27	7.91	13.94	31.06
decay heat	W/m	0.89	1.98	11.04	12.99	12.44	
B_{fixed}	(T)			2	2	2	
(ramp freq)	(kHz)			281	79.83	8.00	
Disp.	m			0.40	0.60	0.80	
βmax	m	0.56	0.95	2.94	5.88	26.00	
$\sigma_z{}^{\mathrm{init}}$	(cm)	9.17	7.51	5.73	4.29	2.55	
$\Delta p/p$ init	(%)	12.10	9.45	4.63	2.44	1.27	
σ_y	cm	0.49	0.51	0.55	0.49	0.57	
σ_x	cm			1.85	1.47	1.02	
Pipe full height	cm	4.88	5.10	5.48	4.88	5.70	
Pipe full width	cm	4.88	5.10	18.52	14.67	10.16	
rf Freq	(MHz)	200	200	200	200	400	
Acc./turn	(GeV)	0.20	0.40	0.17	0.50	4	
Acc. time	(μs)			1	6	62	
η	(%)	5.15	5.36	6.36	2.84	6.92	
Acc. Grad.	(MV/m)	8	8	8	10	10	
Synch rot's		0.62	0.63	1.38	2.29	16.39	
Cavity rad	(cm)	54.37	54.88	54.88	60.47	38.26	
rf time	msec	0.04	0.04	0.04	0.05	0.23	
Tot. peak rf	(GW)	0.12	0.21	0.11	0.57	1.02	2.03
Ave. rf power	MW	0.07	0.13	0.07	0.41	3.52	4.21
rf wall	MW	0.35	0.64	0.26	1.47	10.34	13.07

D. Acceleration for 3 TeV Collider

For a high energy machine, the muons accelerators are physically the largest component and are also probably the most expensive. More work is needed on its design. Table III give an early example of a possible sequence of accelerators for a 3 TeV collider. The initial accelerators, up to 50 GeV, are very similar to those for the high luminosity 100 GeV machine given above (Tb. II), although the transverse emittance is even smaller and the longitudinal a little larger. Again, it would be desirable to design a single 50 GeV front end that could meet all three requirements.

1. Magnet Systems

For the final three stages, pulsed magnet synchrotrons [7] are used. In the 200 GeV ring, all the magnets in the ring are pulsed, but in the two last rings a superconducting-pulsed hybrid solution is needed. In these cases, if only pulsed magnets were used, then the power consumed would be too high; and because only low pulsed fields could be used, the circumferences would also be very large. It is thus proposed to use rings with alternating warm pulsed magnets and superconducting fixed magnets [8] (see figure 2). The fixed magnets are superconducting at 8 T; the pulsed magnets are warm with fields that swing from - 2 T to + 2 T. The effective ramp frequency is given in the table. By choosing appropriate ratios of fixed and pulsed magnets, the last two such rings can be located in the same tunnel.

Designs of suitable pulsed magnets [8](see Fig. 1 have been shown to have sufficiently low losses for this application. The magnets employ cables made of many fine insulated strands (litz cable) and the yokes are made of very thin (.28 mm), 3% Si-Fe laminations, possibly of Metglas [9,10] for the higher rate cases.

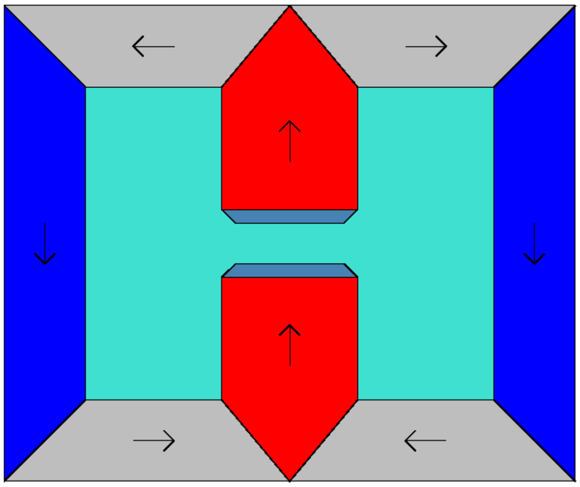

FIG. 1. A 2-d picture of an H frame magnet lamination with grain oriented 3 % Si-Fe steel.The arrows show both the magnetic field and the grain direction.

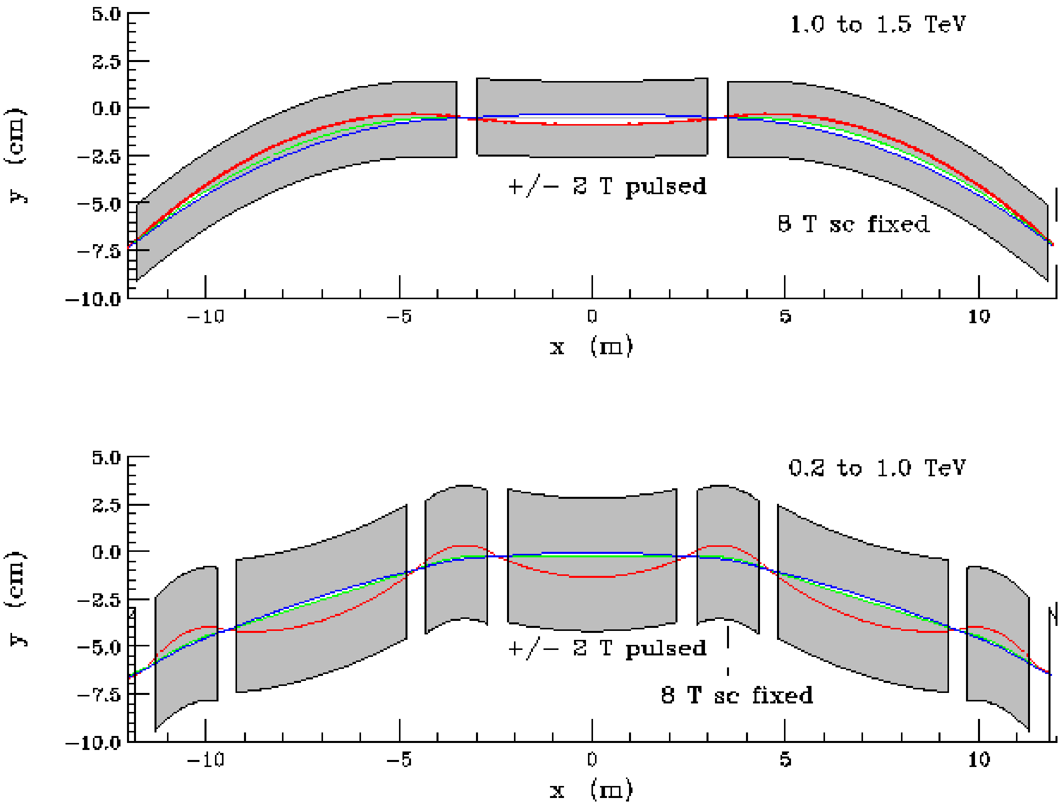

FIG. 2. Schematic of hybrid superconducting-pulse magnet accelerator ring

2. RF Systems

In all the final three rings superconducting rf is employed to minimize the peak power requirements. In the final rings this is also important to obtain high wall to beam efficiency and thus keep the wall power consumption reasonable. In the final two rings the frequency and cavity d esigns are chosen to be the same as that in the TESLA [11] proposal. Higher orer mode damping will have to be studied to see if modifications are needed.

TABLE III. Parameters of Acceleration for 3 TeV Collider

Acc. type		linac	recirc	recirc	recirc	recirc	synch	synch	sums
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	29.52
Turns		2	8	10	11	15	27	17	
Loss	(%)	6.11	12.28	10.84	13.94	10.68	10.07	2.65	50.58
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	
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	
$\Delta p/p^{\mathrm{init}}$	(%)	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	msec	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	5.51
Ave. rf power	MW	0.14	0.25	0.45	11.04	6.32	21.91	15.07	55.18
rf wall	MW	0.64	0.88	1.62	32.47	18.59	44.72	30.76	130

E. Simulations

A study [12] followed the longitudinal motion of particles through a similar sequence of recirculating accelerators (for a 4 TeV collider in this case). rf cavities similar to those proposed for TESLA [11] were assumed. Figure 3 shows, after optimization of parameters, the final longitudinal phase space distributions corresponding to wake fields estimated for four different bunch charges: a) very small, b) 0.83×10^{12} muons, c) 2.08×10^{12} muons, and d) 4.17×10^{12} muons.

For the design beam charge of 2×10^{12} muons (approximately as for Fig. 3(c) the wakefield amplitude was estimated to be 2.5 MV/m, the accelerating phase used was 35^o, and rf voltage depression 26 %. The simulation used an initial longitudinal phase space 20 eV-s. It gave negligible particle loss, a final longitudinal phase space was 21.6 eV-s, and thus an increase of longitudinal emittance of only 8 %.

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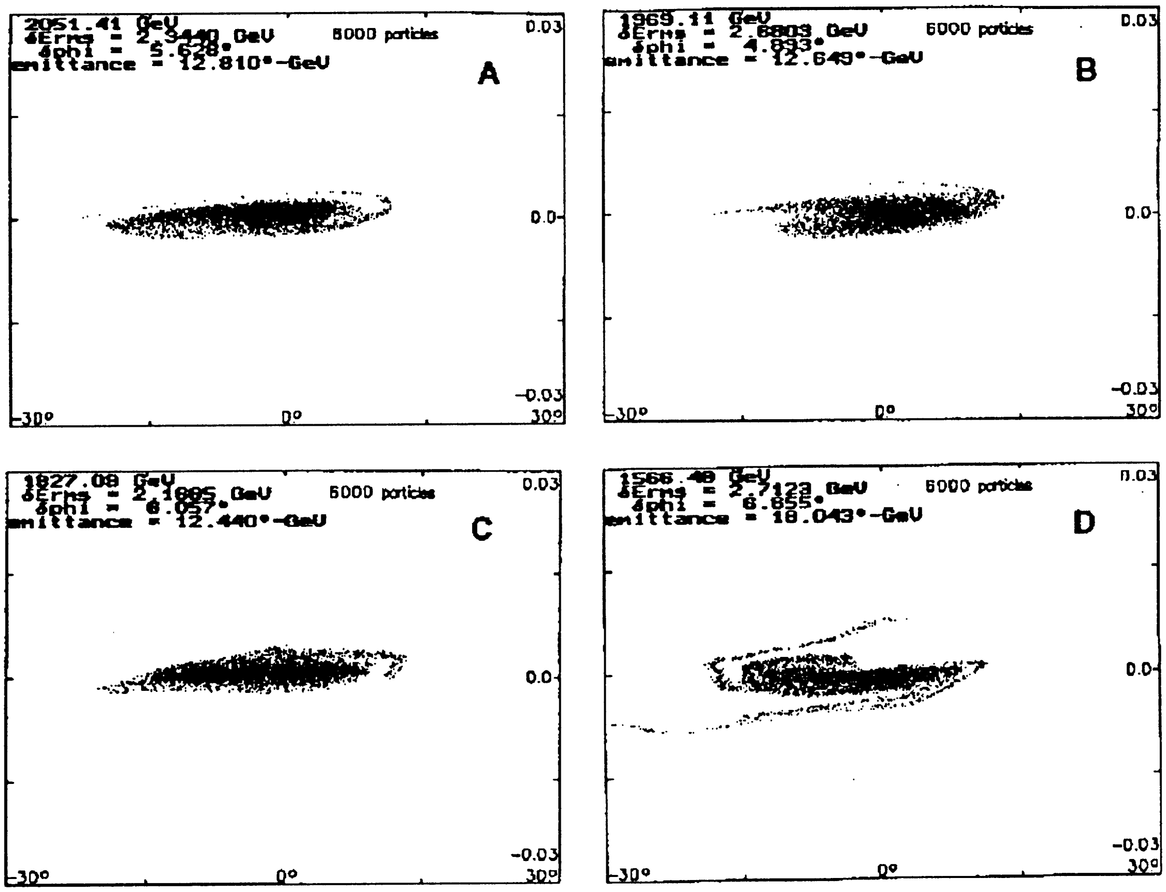

FIG. 3. μRLA simulation results with wake fields, with beam accelerated from 200 to 2000 GeV in a 10-turn RLA.

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