LARGER CIRCULAR COLLIDERS

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Two types of circular colliders are discussed, muon colliders, and hadron colliders. In both cases, typical values of the most relevant parameters are presented, the state of component development is discussed, schedules for the earliest dates of construction are shown, and critical issues needing R&D are mentioned.

1 Introduction

In this talk, I shall restrict myself to high-energy colliders, in particular linear e^+e^- colliders, muon colliders, and hadron colliders. I discuss them in Chapters, 2 and 3, respectively.

2 Muon Colliders

The possibility of muon colliders was introduced by Budker¹, Parkhomchuk and Skrinsky², and Neuffer³. It has been developed intensively over the past three years^{4,5,6,7,8}. A feasibility study for a 4 TeV muon collider was presented at Snowmass⁹, and a formal collaboration was set up recently¹⁰.

2.1 Muon Collider Components

Fig. 1 shows a schematic layout of a $\mu^+\mu^-$ collider complex. A powerful proton synchrotron accelerates a few short proton bunches that hit a small target for copious π production. A system of solenoids and RF cavities captures and accelerates the π 's and μ 's. An ionisation cooling channel reduces the six-dimensional phase space volume of the μ beam by a factor between 10^5 and 10^6 . A cascade of recirculating linear accelerators similar to CEBAF rapidly accelerates the $\mu^+\mu^-$ to the collision energy. They are finally stored in a collider ring. The $\mu^+\mu^-$ collisions occur in a fancy low- β insertion.

Tab. 1 compares the parameters of a typical proton source for a $\mu^+\mu^-$ collider with the proton source projects KAON¹¹, JHF¹², ESS¹³, and existing proton synchrotrons. Some of them provide the proton energy E , some the repetition frequency f , and some the beam power P , but none achieves the combination of E , f and P needed for a $\mu^+\mu^-$ collider.

Figure 1: Schematic 4 TeV $\mu^+\mu^-$ Collider: The main components are the proton source, $\mu^+\mu^-$ production, ionization cooling, fast acceleration, and the collider ring. The diagram is not to scale.

Table 1: Energy E , repetition rate f and beam power P of a typical proton synchrotron for $\mu^+\mu^-$ production, and of the KAON, JHF, ESS projects and existing machines

Machine	E/GeV	f/Hz	P/MW
$\mu^+\mu^-$ PS	16	15	4
KAON	30	10	3
JHF	50	0.3	0.5
ESS	1.33	50	5
FNAL booster	8	15	0.067
CPS	28	0.4	0.056

2.2 Muon Collider Ring

The most important parameters of a $\mu^+\mu^-$ collider ring appear in the following equation for the luminosity $\bar{L}$, averaged over the relativistic μ lifetime:

$$\bar{L} = \left(\frac{\tau_0}{e\mu_0} \right) \dot{N}_\mu \left(\frac{\xi\gamma B}{\beta_\perp} \right) \left(\frac{2\pi\rho}{C} \right) \quad (1)$$

The first bracket contains the natural constants μ lifetime at rest $\tau_0 = 2.19703 \pm 0.00004 \mu\text{s}$, μ charge e , and permittivity of free space μ_0 . Then comes the $\mu^+\mu^-$ storage rate $\dot{N}_\mu$, determined by the $\mu^+\mu^-$ source. The second bracket contains the beam-beam tune shift parameter ξ , the relativistic factor γ , the dipole field in the arcs B , and the value of the β -function at the interaction point $\beta_\perp$. The last bracket is a filling factor < 1 , the ratio of the total length of dipoles in the arcs $2\pi\rho$ and the ring circumference C . Only two assumptions enter into (1): The interval between fills is long compared to the relativistic μ lifetime, and the beams are round at the interaction point. For good average luminosity $\bar{L}$, the quantities in the numerator should be large, and those in the denominator small.

Tab. 2 shows the parameters of $\mu^+\mu^-$ colliders at two energies, a high energy one with 3 TeV in the CoM, and a lower energy ‘‘Higgs factory’’ at 100 GeV in the CoM. Because of their larger mass, μ ’s produce much less synchrotron radiation than electrons of the same energy, and can be recirculated and stored in circular machines at high bending field. Hence, $\mu^+\mu^-$ colliders are much more compact than circular e^+e^- colliders at the same energy. The 3 TeV $\mu^+\mu^-$ collider has about the size of the SPS at CERN with $C = 6911$ m, while the e^+e^- collider LEP at CERN with 200 GeV in the CoM has $C = 26659$ m. The arcs of a $\mu^+\mu^-$ collider have a high dipole field in order to maximise the number of turns in the $\mu^+\mu^-$ lifetime. They are nearly-isochronous in order to achieve short bunches. The low- β insertion uses techniques from final-focus systems of linear e^+e^- colliders to achieve a low value of $\beta_\perp$ at the

Table 2: Parameters of $\mu^+\mu^-$ colliders

CoM Energy (GeV)	3000	100	
No. of $\mu^\pm$ bunches/sign	2	1	
Bunch population (10^{12})	2	4	
Collider circumference (m)	6000	300	
RMS momentum spread(%)	0.16	0.12	0.003
Free space ℓ^* at IP (m)	6.5	5	
β^* at IP (cm)	0.3	4	13
Bunch length σ_z (cm)	0.3	4	13
Beam radius at IP (μm)	3.2	82	270
Beam-beam tune shift ξ	0.043	0.05	0.015
Luminosity (nbs) $^{-1}$	50	0.12	0.01

interaction point IP where the detector is installed. The projected beam-beam tune shift ξ is higher than in hadron colliders, and comparable to that of e^+e^- colliders.

2.3 Critical $\mu^+\mu^-$ Collider Issues

Many of the components of a $\mu^+\mu^-$ collider system are at the limit of what is technologically possible. These components should be tested one by one. A proposal for an initial cooling experiment was submitted to Fermilab¹⁵. A proposal for a targetting experiment at BNL is being prepared.

Collimated neutrino beams from muon decay in straight section are a radiation hazard, imposing upper limit on muon energy and lower limit on depth of $\mu^+\mu^-$ collider.

3 Future Larger Hadron Colliders

Future larger hadron colliders beyond the LHC and the discontinued SSC were discussed in 33 Eloisatron studies at Erice¹⁶ since 1986, and in ‘VLHC’ workshops at Indianapolis and Snowmass¹⁷ since 1996. Exploratory studies continue in several laboratories^{18,19,20}. A National vlhc Organization was recently set up in the US with a steering committee, working groups, meetings, etc.²¹.

3.1 FLHC Studies

Tab. 3 compares the parameters of the LHC with those of three larger machines, a 50 TeV collider LoB with 1.8 T dipoles¹⁷, a 50 TeV collider HiB with 12.6 T dipoles¹⁷, and a 100 TeV collider with 12 T dipoles¹⁶. The combination of a high

and a low dipole field B , and of two energies E , and the comparison with the LHC, clearly show how the choice of B and E changes the parameters. The stored energy is given in tons of TNT. The conversion factor is 1 t TNT $\equiv$ 4.7 GJ. The LoB collider has combined-function arcs. Hence, it is anti-damped, and the damping time is negative, but long enough.

Table 3: Comparison of LHC and FLHC Parameters

	LHC	LoB	HiB	E12T
Beam energy/TeV	7	50	50	100
Dipole field/T	8.4	1.8	12.6	12
Circumference/km	27	646	104	229
Luminosity/(nbs) $^{-1}$	10	10	12	10
Bunch spacing/ns	25	16.7	16.7	37.5
Events/collision	19	10	12	23
Vert. damping time/h	26	−ve	2.6	1.5
Radiation power/kW	3.7	48	189	1080
Stored energy/t TNT	0.07	2.07	0.19	0.63
Debris power/kW	0.8	4.8	5.8	9.6

Contrary to a $\mu^+\mu^-$ collider system, the scale of an FLHC system is dominated by the collider ring proper, not by its injectors. The number of events in a collision, $n_c = L\sigma_{\text{inel}}s$, expresses the ease or difficulty of analyzing the events in the detector, with inelastic cross section σ_{inel} . Keeping it at values comparable to those for LHC essentially imposes an upper limit on the bunch spacing s . The power in the debris $D = L\sigma_{\text{inel}}E$ of the collisions, which must be absorbed by shielding to prevent the cascades from heating super-conducting coils, is given by the performance parameters, leaving no choice for the designer.

3.2 Critical FLHC Issues

The product of damping time τ_z and damping partition number J_z for synchrotron radiation in the arbitrary z -plane is:

$$\tau_x J_x = \left(\frac{3E_0^3}{e^2 c^3 r_c} \right) \frac{1}{EB^2} \left(\frac{C}{2\pi\rho} \right) \quad (2)$$

Here E_0 is the rest mass of the particle and r_c its classical radius. Numerically the factor in the left bracket is 16644 h TeV T². The right bracket is the reciprocal of the filling factor appearing in (1). By using (2), the synchrotron radiation power P , that may cause a considerable heat load when it gets absorbed in a vacuum chamber at

cryogenic temperatures, and the stored energy in one beam G , that must be absorbed by a beam dump without destroying it, can be brought into the following forms:

$$P = \left(\frac{4\pi r_c^{3/2}}{\sqrt{3cE_0}} \right) \frac{E^{3/2} L \beta_{IP}}{\xi \sqrt{J_z \tau_z}} \sqrt{\frac{C}{2\pi\rho}} \quad (3)$$

$$G = \left(\frac{2\pi r_c^{3/2}}{\sqrt{3cE_0}} \right) \frac{E^{3/2} L \beta_{IP} \sqrt{J_z \tau_z}}{\xi} \sqrt{\frac{C}{2\pi\rho}} \quad (4)$$

The central fraction in (3) and (4) contains the design parameters E , L , β_{IP} , and ξ , and opposite powers of $\sqrt{J_z \tau_z}$. By choosing B , and hence τ_z , one can trade a reduction of P against and increase of G , and vice-versa.

An important collective effect is the transverse resistive-wall instability²⁰. Its growth rate is a function of the conductivity, and hence depends on the composition and temperature of the vacuum chamber. By choosing the temperature, one can trade the growth rate of the instability and the feedback system needed to damp it against the heat load caused by the synchrotron radiation absorbed by the vacuum chamber. A second important collective effect is the coherent synchrotron tune shift, driven by the longitudinal broad-band impedance²⁰. In order to ensure longitudinal Landau damping, the bunch length must be increased. In the high B colliders, the growth times caused by intra-beam scattering are only a little larger than the damping times²⁰.

Simply scaling the FLHC cost from LEP, LHC and/or SSC would result in ex-orbitant figures. Therefore, R&D programmes, aiming at significant reductions of unit prices, have been launched. In the US, they are coordinated by the National vlhc Organization. Figs. 2 and 3 show examples of magnet designs at LBNL²² and Fermilab²³.

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Figure 2: Concept of Half a High B Dipole at LBNL: The coils and beam apertures are in the upper and lower part of the the rectangular region to the left. The half circle is the steel yoke with magnetic field lines. The colour code shows its saturation.

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Figure 3: Model of Low B Dipole at Fermilab: The upper part shows the dipole proper with the left extruded Al beam pipe and the super-conducting 75 kA transmission line. The lower part shows the structural support tube, the cryoline vacuum jacket, the current return line, and the cryogenic piping for the distribution of single-phase He along the ring.