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Proton colliders at the energy frontier

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ABSTRACT

Since the first proton collisions at the CERN Intersecting Storage Rings (ISR) (Johnsen, 1973; Myers, 2010) [1,2], hadron colliders have defined the energy frontier (Scandale, 2014) [3]. Noteworthy are the conversion of the Super Proton Synchrotron (SPS) (Hatton, 1991; Evans, 1988) [4,5] into a proton–antiproton collider, the Tevatron proton–antiproton collider (Lebedev and Shiltsev, 2014) [6], as well as the abandoned SSC in the United States (Jackson et al., 1986; Wienands, 1997) [7,8], and early forward-looking studies of even higher-energy colliders (Keil, 1992; Keil, 1997; Barletta and Leutz, 1994; The VLHC Design Study Grup (Ambrosio et al.) 2001) [9–12]. Hadron colliders are likely to determine the pace of particle-physics progress also during the next hundred years. Discoveries at past hadron colliders were essential for establishing the so-called Standard Model of particle physics. The world's present flagship collider, the Large Hadron Collider (LHC) (Brüning et al., 2004) [13], including its high-luminosity upgrade (HL-LHC) (Apollinari et al., 2017) [14], is set to operate through the second half of the 2030's. Further increases of the energy reach during the 21st century require another, still more powerful hadron collider. Three options for a next hadron collider are presently under investigation. The Future Circular Collider (FCC) study, hosted by CERN, is designing a 100 TeV collider, to be installed inside a new 100 km tunnel in the Lake Geneva basin. A similar 100-km collider, called Super proton–proton Collider (SppC), is being pursued by CAS-IHEP in China. In either machine, for the first time in hadron storage rings, synchrotron radiation damping will be significant, with a damping time of the order of 1 h. In parallel, the synchrotron-radiation power emitted inside the cold magnets becomes an important design constraint. One important difference between FCC and SppC is the magnet technology. FCC uses 16 T magnets based on Nb_3Sn superconductor, while SppC magnets shall be realized with cables made from iron-based high-temperature superconductor. Initially the SppC magnets are assumed to provide a more moderate dipole field of 12 T, but they can later be pushed to a final ultimate field of 24 T. A third collider presently under study is the High-Energy LHC (HE-LHC), which is a higher energy collider in the existing LHC tunnel, exploiting the FCC magnet technology in order to essentially double the LHC energy at significantly higher luminosity.

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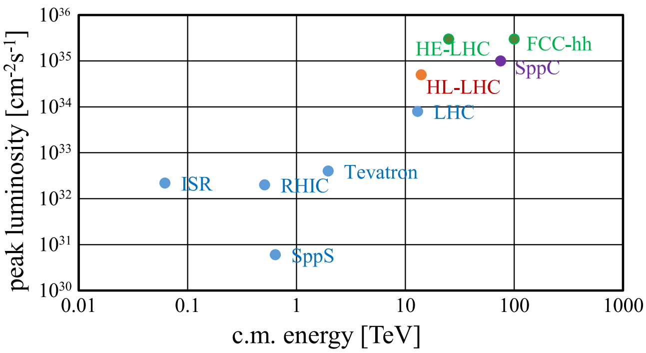

Fig. 1. Luminosity vs. center-of-mass energy for past and present [blue], upcoming [red], and longer-term future hadron (pp or $p\bar{p}$) colliders [green and purple] around the world. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1. Introduction

Circular hadron colliders are known as discovery machines. Their discovery reach is determined by the beam energy, which depends on only two parameters: the dipole magnetic field and the size of the collider. Therefore, historically new colliders always were larger and used stronger magnets than their predecessors [1–14]. For example, the Tevatron near Chicago was the first hadron collider based on superconducting magnet technology, with a dipole field of 4.2 T, and it was installed in a 6.3 km ring [6]. The LHC uses 8.3 T dipoles in a 26.7 km tunnel [13]. The 100 TeV Future Circular Collider (hadron version "FCC-hh") requires 16 T dipole magnets in a 100 km ring. No other proposed concept, not even a muon collider or a plasma collider, appears technically ready to provide collision energies in the 10's of TeV energy range during the 21st century.

The collider luminosity ideally increases with the square of the energy since the cross sections decrease as the inverse square of energy. However, due to the nonlinear parton distribution inside the colliding protons also a lower luminosity can produce exciting physics, and the most important parameter of a hadron collider remains its energy. Nevertheless, at a given energy the discovery reach grows with higher luminosity [15]. which is one of the motivations for upgrading the LHC to the HL-LHC [14]. The LHC design has already dramatically increased the luminosity compared with previous machines. This can be seen in Figs. 1 and 2. Much higher luminosities still are expected for the approved HL-LHC, which will lower its peak luminosity by "levelling" in order to make it acceptable for the physics experiments, as well as for the proposed HE-LHC and FCC-hh. The luminosity for the latter two machines will profit from significant radiation damping at the associated high beam energies and magnetic fields [16].

2. Hadron-collider beam dynamics and limitations

The hadron-collider luminosity increases linearly with energy due to the shrinking beam sizes, when keeping the beam current, the beta functions at the interaction point (IP), $\beta^*_{x,y}$, and the beam–beam tune shift constant. Even higher luminosity can be achieved by reducing the IP beta functions. Perhaps surprisingly, until now all hadron colliders, starting from the ISR, have operated with similar beta functions, with minimum values of about 0.3 m; see Table 1. With 0.15 m (or even 0.10 m) the HL-LHC will set a new record. An ongoing study aims at pushing the FCC-hh β^* down to 5 cm [17].

For proton–proton colliders with many bunches, such as HL-LHC and FCC-hh, a crossing angle is required to avoid or mitigate parasitic beam–beam collisions. Unfortunately, this crossing angle needs to be increased as $\beta^*_{x,y}$ is reduced. Without countermeasures this would dramatically degrade the geometric overlap of the colliding bunches and all but

Table 1
Beta* at hadron colliders (R. Tomas [24]).

Collider	β^*_x [m]	β^*_y [m]
ISR	3.0	0.3
$Sp\bar{p}S$	0.6	0.15
HERA-p	2.45	0.18
RHIC	0.50	0.50
Tevatron	0.28	0.28
LHC	0.3	0.3
HL-LC	0.15	0.15
FCC-hh	1.1→ 0.3 (0.05)	1.1→ 0.3 (0.05)
SppC	0.71	0.71
HE-LHC	0.25	0.25

Table 2
Parameters of future hadron colliders, the LHC and its HL-LHC upgrade. The HL-LHC will level the luminosity at a value of 5×10^{34} cm^{-2} s^{-1}, for the particle-physics experiments; its virtual peak luminosity is about 5 times higher.

Parameter	FCC-hh		SppC	HE-LHC	(HL-)LHC
C.m. energy [TeV]	100		75	27	14
Dipole field [T]	16		12	16	8.3
Circumference [km]	97.8		100	26.7	26.7
Beam current [A]	0.5		0.77	1.12	(1.12) 0.58
Part./bunch [10^{11}]	1		1.5	2.2	(2.2) 1.15
Bunch spacing [ns]	25		25	25	25
Norm. emittance ε_N [μm]	2.2 (1.1)		3.16	2.5 (1.25)	(2.5) 3.75
IP beta function [m]	1.1	0.3	0.71	0.25	(0.15) 0.55
Lum. [10^{34} cm^{-2} s^{-1}]	5	30	10	28	(5, lev.) 1
Events per crossing	170	1000	~300	800	(135) 27
SR power/beam [kW]	2400		1130	100	(7.3) 3.6
Longit. damp. time [h]	1.1		2.4	3.6	25.8
Init. burn-off time [h]	17	3.4	13	3.0	(15) 40

eliminate any benefit from reducing the IP beam size. To avoid this degradation, the HL-LHC, the HE-LHC and FCC-hh phase 2 will all use novel crab cavities [18–23]. These are transversely deflecting RF cavities, which impart kicks of opposite sign to the head and the tail of each bunch, so as to maintain the crossing angle of the bunch centroid motion, while at the same time restoring the full geometric bunch overlap during the collision.

Present and future hadron colliders are characterized by a large amount of stored beam energy, which render machine protection a paramount concern. A multi-stage collimation system is needed to avoid local beam loss spikes near cold magnets, which would induce magnet quenches. The collimation system of the LHC [25] works according to specification [26]. For the planned and proposed future colliders –HL-LHC, HE-LHC, SppC, and FCC-hh –collimation remains a challenge.

Beam injection and beam extraction are particularly sensitive operations, as the injection or dump kickers belong to the fastest elements in the machine. The collider design must be robust against the sudden asynchronous firing of a kicker unit. The collimators are likely to be the first element to be hit by the beam in case of any fast failure. They must withstand the impact of one or a few bunches. The primary and secondary collimators of the LHC are based on carbon–carbon composite material. For the HL-LHC and farther future machines, even stronger materials are being developed and examined, which, in addition, feature a higher conductivity and, hence, lower "impedance". More advanced options include the use of short bent crystals as primary collimators, and the deployment of hollow electron-beam lenses as non-destructible collimators. An acceptable performance of the collimation system along with small IP beta function also requires an excellent optics control.

Hadron beam intensity may be limited by conventional instabilities, in particular, due to the very large circumference and low momentum compaction, respectively, by resistive wall instability (low revolution frequency) and transverse mode coupling at injection. Another intensity limit may arise from the build up of an electron cloud, which may drive a different type of instability or create additional significant heat loads on