A very high energy hadron collider on the Moon

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The long-term prospect of building a hadron collider around the circumference of a great circle of the Moon is sketched. A Circular Collider on the Moon (CCM) of ∼11000 km in circumference could reach a proton-proton center-of-mass collision energy of 14 PeV — a thousand times higher than the Large Hadron Collider at CERN — optimistically assuming a dipole magnetic field of 20 T. Siting and construction considerations are presented. Machine parameters, powering, and vacuum needs are explored. An injection scheme is delineated. Other unknowns are set down. Through partnerships between public and private organizations interested in establishing a permanent Moon presence, a CCM could be the (next-to-) next-to-next-generation discovery machine and a natural successor to next-generation machines, such as the proposed Future Circular Collider at CERN or a Super Proton-Proton Collider in China, and other future machines, such as a Collider in the Sea, in the Gulf of Mexico. A CCM would serve as an important stepping stone towards a Planck-scale collider sited in our Solar System.

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I.   INTRODUCTION

After the discovery of the Higgs boson by the ATLAS and CMS collaborations in 2012 [1, 2], high-energy particle physics finds itself with two main goals for the future. The first is to accomplish a high-precision study of the Higgs and other Standard Model particles and parameters. The second is to attain higher center-of-mass collision energies with hadrons, to explore unexplored parameter space and open up the prospect of new particle discoveries. Both of these goals are the foci of the proposed next-generation circular collider projects such as the Future Circular Collider (FCC) [3–5] at CERN; the Circular Electron-Positron Collider (CEPC) and its potential successor, the Super Proton-Proton Collider (SPPC) [6–9] in China; or, more exotically, a Collider in the Sea (CitS) floating in the Gulf of Mexico, as has been proposed by a few U.S.-based collider experts [10]. During eventual proton-proton collisions, these machines could reach center-of-mass energies of 80–120 TeV (or 500 TeV in the case of the CitS), a substantial increase over the current energy of 13 TeV at the Large Hadron Collider (LHC).

However, the state of particle physics after the Higgs discovery is such that there are multiple unsolved mysteries of physics, but few (or no) hints as to the mass scale of new particles or phenomena, that, if discovered, could help solve these. New particles could appear at any energy up to the Planck energy, 10^{16} TeV. The future of collider physics is exploratory and experimental, irrespective of specific theory motivation. The physics cases for an FCC, a CEPC/SPPC, and a CitS are clear, but stretching beyond those projects requires exploratory experiments that reach as high a center-of-mass collision energy as possible.

Building a hadron collider much larger than those proposed for the next generation (of ∼80–100 or 1900 km in circumference) on Earth will likely prove politically and geographically challenging to a prohibitive degree.

In contrast, the Moon presents a potentially ideal site for the next great step forward in collider physics. Both NASA and private companies are interested in establishing a permanent presence on the Moon, and the U.S. Department of Energy has encouraged the international particle physics community to collaborate in this endeavor [11]. This evinces the possibility of a Moon-based PeV-scale collider.

Indeed, through its Artemis program [12], launched in 2017, NASA aims at establishing a sustainable presence on the Moon by 2028. In preparation for this, Moon deliveries are already starting as early as 2021, in the frame of the Commercial Lunar Payload Services (CLPS) initiative [13]. The near-term goal is to explore the entire surface of the Moon with human and robotic

explorers. This exploration will provide relevant information for optimizing the placements of future large-scale lunar infrastructures. Potential materials and structural concepts for second-generation habitat construction on the Moon are also rather well established already. For example, Ref. [14] discusses a simple structural frame for erection and concludes that a lunar habitat can be built with a reasonable factor of safety and using existing technology.

In this document, we examine the prospect and challenges of building a hadron collider around the ∼11000-km circumference of a great circle of the Moon, a Circular Collider on the Moon (CCM). A CCM could be made 100 times larger than the proposed FCC in the Lake Geneva Basin on Earth and would be six times larger than a CitS. Optimistically assuming a dipole magnetic field of 20 T, a CCM could potentially reach a proton-proton center-of-mass collision energy of 14 PeV, a thousand times more energetic than the LHC.

II.   CONSTRUCTION AND SITING

Two primary considerations for a CCM are its method of construction and its location on the Moon. The advantages, disadvantages, and costs of constructing a tunnel a hundred to several hundred meters under the surface, fully circumnavigating the Moon ("tunnelling", i.e., using lunar tunnel boring machines), vs. excavating a shallower trench and then covering it ("cut-and-cover") or constructing on the surface, would need to be studied, and an appropriate placement to be identified. Presented here are initial investigations as to the pros and cons of methods of construction and locations for a CCM. For future refinement, using, for example, the Unified Geological Map of the Moon [15] along with further information expected from NASA's Artemis program [12], as an input, the placement on the Moon could be optimised by applying the Tunnel Optimisation Tool, which was developed in the frame for the FCC study [16].

A.   Method of construction

Temperature extremes on the Moon present a challenge for a CCM. The dipole magnets needed to accelerate protons must be superconducting, which requires low temperatures compared to, e.g., room temperature on the surface of the Earth. When exposed to the sun, the temperature on the lunar surface can reach $\sim$127 °C [17] ($\sim$400 K), too high to consider any superconducting magnets. However, during Moon night, the temperature drops to about -173 °C ($\sim$100 K). This is approximately the temperature at which high-temperature superconductors (HTSs) could operate. This suggests one possible CCM scenario, Scenario A: Build the collider on the surface, charge an energy storage system during the lunar day, and operate the collider at night when the magnets are superconducting. The challenge with this scenario is that lunar days and nights last 13.5 Earth days each, leading to long stretches of non-operation. Scenario A has the benefit of avoiding the need to dig a tunnel, typically a large cost for any collider project.

Scenario A would also require a tunnel diameter D somewhat smaller than twice the Moon radius $2R$ to ensure that the entire tunnel experiences Moon night at the same time. The fraction of the Moon night covering the entire collider can be estimated as $[\pi - 2\arcsin(D/(2R))]/(\pi R)$, which vanishes for $D = 2R$.

In addition to the above challenges, Scenario A also leaves the CCM exposed to not just extreme temperatures, but also to meteoroid strikes, which could potentially cause substantial damage to surface equipment. The Moon is bombarded by smaller meteroids regularly, resulting in numerous

strong impacts each year that leave craters from a few centimeters to ∼10 m in diameter [18]. (Impacts larger than this are rare.) A CCM constructed under Scenario A, i.e., on the lunar surface, would need to be adequately shielded to withstand impacts from small meteroids moving at up to 500 m per second [19]. Such shielding should in principle be possible to achieve, though further study would be needed.

The drawbacks related to temperature variations and potential meteroid damage could be obviated by other scenarios. For example, in Scenario B a CCM could be constructed by digging and covering a trench a few meters deep (cut-and-cover). According to measurements from the Apollo 15 and 17 missions [20], temperature fluctuations due to lunar day-night temperature cycles are negligible once one reaches ∼50 cm below the lunar surface, as shown in Figure 1.
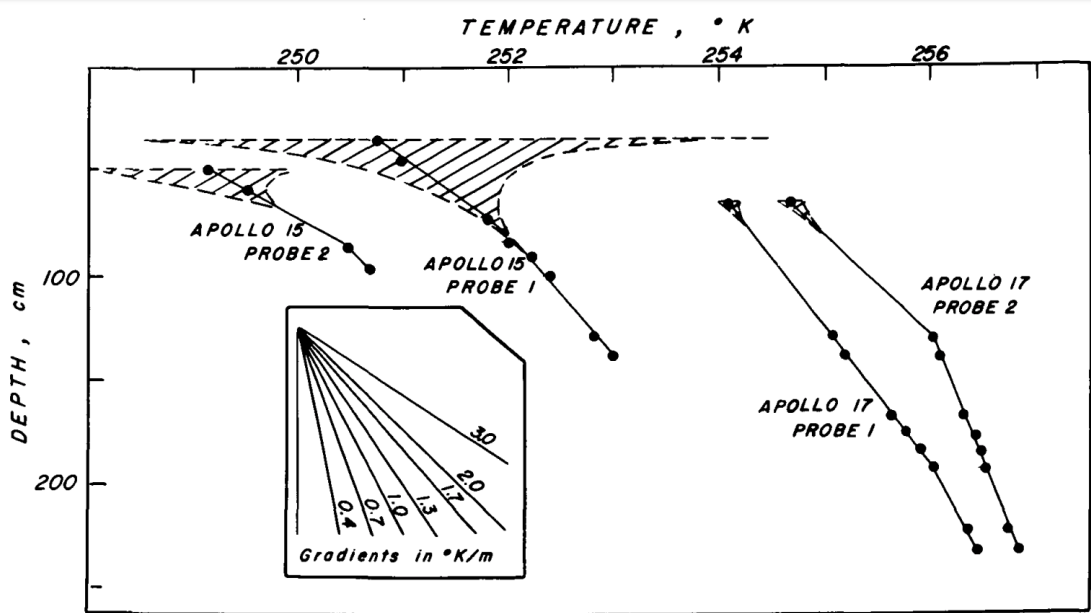

FIG. 1. Temperature, in K, of the lunar subsurface, as measured by the Apollo 15 and 17 missions, taken directly from Ref. [20]. The striped regions for depths less than ∼70 cm show the variations in temperature measured throughout a lunar month. At depths exceeding ∼50 cm, temperature fluctuations due to lunar day-night cycles are negligible.

However, the temperature of the lunar subsurface, while constant throughout lunar day and night, is still too high for presently known HTS materials, at 255–256 K at a depth of 1–2 m. Thus, a cooling system will be needed to maintain the HTS at a temperature of order 100 K and to enable CCM operation during lunar day and night for any scenario other than Scenario A. Additionally, it is possible that Scenario B by itself would not provide adequate shielding to protect against damage from meteoroid strikes, and that further surface shielding would need to be constructed

anyway.

In a third scenario, Scenario C, a CCM tunnel could be bored a few tens to a few hundred meters under the lunar surface. Such tunnel boring would add substantial cost and time to the project and would still require a magnet cooling system, but would definitely prevent damage from (most) meteoroid strikes. Additionally, there has been much prior discussion of constructing tunnels for lunar habitats [21], including the planned development of lunar tunnel boring machines [22–24] operated remotely from Earth, and of the utilization of existing lunar lava tubes [25, 26], and, thus, Scenario C would present key opportunities for collaboration with other organizations and initiatives.

B.   Placement and site

The Moon has been measured to be a slightly scalene spheroid [27], but for our purposes we model it as a sphere with a radius of 1738 km [28] and thus circumference of 10921 km, the equatorial circumference. More significant for a CCM is the fact that the lunar surface is rather rough. Local topographical deviations from an overall spherical shape can be large. The side of the Moon facing the Earth (the near side) is much smoother than the far side, where the largest deviations occur, with maximum elevations of ∼10.8 km [29] and minimum elevations of approximately −9.1 km [30] relative to a reference sphere. (For reference, the highest mountain on Earth is Mt. Everest at an elevation of 8.8 km and the deepest part of the ocean is the Challenger Deep section of the Mariana Trench, at a depth of ∼11 km. However, Earth's radius is 3.7 times greater than the Moon's.)

To ensure accessibility for maintenance and repairs, it will be beneficial to identify a CCM trajectory that avoids large elevation changes as much as possible. One such trajectory is shown schematically in Figure 2.

This trajectory circumnavigates the Moon approximately around the outer edge seen from the Earth, but slightly displaced toward the Earth. Such a trajectory appears to potentially avoid several major elevation changes, although not all. Irrespective of whether a tunnel a few hundred meters underground is bored (Scenario C) or a cut-and-cover approach is taken (Scenario B), the construction of a CCM will likely require some tunneling. Other major features, particularly the large *mare* (Mare Humboldtianum) [37] in the northern lunar hemisphere, will likely require the CCM beam pipe and tubular shielding structure to be suspended, potentially several kilometers above the sunken surface. A detailed survey of this and other potential CCM sites is left for future work.
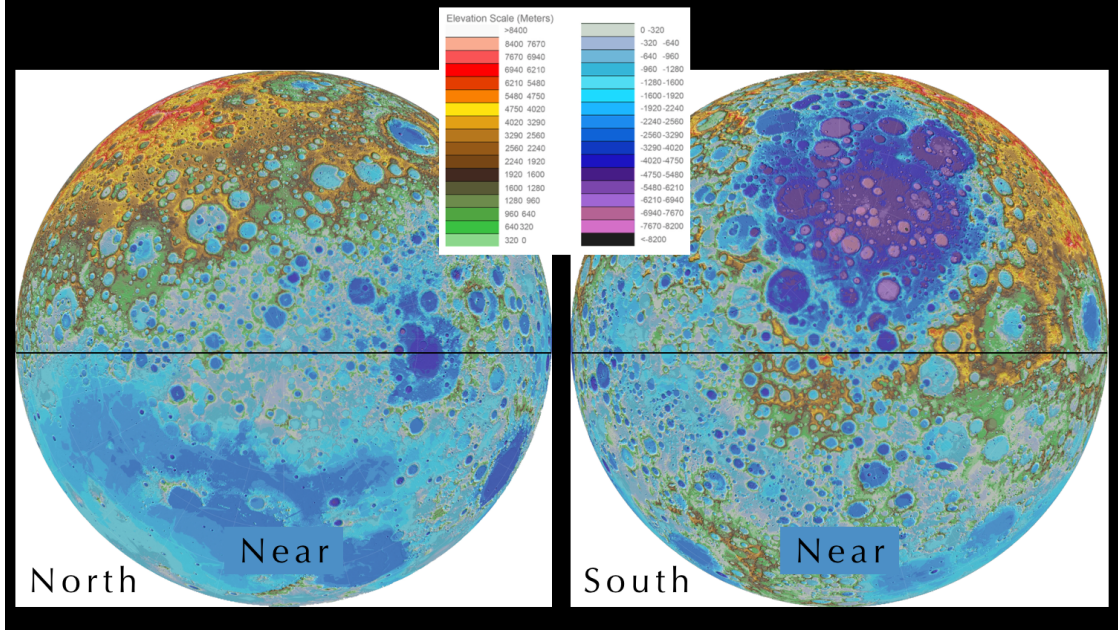
FIG. 2. Schematic possible trajectory (black line) of a Circular Collider on the Moon (CCM) that could potentially avoid several major elevation changes, though not all. In the left image the north pole of the Moon is centered, while in the right image the south pole is centered. Images modified from Ref. [31]; the originals were constructed with data collected by the Lunar Reconnaissance Orbiter [32–36].

III. MACHINE PARAMETERS, POWERING, AND MOON CONSIDERATIONS

A. CCM machine parameters

Since the strong and electromagnetic cross sections decrease as $1/\gamma^2$ (where γ is the Lorentz factor of the accelerated protons), the luminosity should increase with the square of the energy. Extrapolating from the FCC-hh (with a peak luminosity of about 3×10^{35} cm^{-2}s^{-1} at $\sqrt{s} = 100$ TeV), a 14 PeV collider should aim at the much higher luminosity of 6×10^{39} cm^{-2}s^{-1}. The collider luminosity can be expressed as

$$L = \frac{f_{\mathrm{rev}} n_b N_b}{4\pi \sigma_x^* \sigma_y^*} F_{\mathrm{geom}} \tag{1}$$

with $\sigma_x^* = \sigma_y^* = \sqrt{\beta_{x,y}^* \varepsilon_{x,y}}$ the rms beam size at the interaction point (IP), n_b the number of bunches per beam, N_b the bunch population, f_{rev} the revolution frequency, and $F_{\mathrm{geom}} \approx 1$ a geometric factor taking into account the so-called hourglass effect (variation of the beta function across the luminous region), crossing angle, etc. We can rewrite the luminosity by introducing the beam current $I_{\mathrm{beam}} = e n_b N_b f_{\mathrm{rev}}$ and the beam-beam tune shift ξ for round beams colliding head-on,

$$\xi = \frac{r_p N_b}{4\pi \varepsilon \gamma} \,, \tag{2}$$

where γ denotes the relativistic Lorentz factor (here $\gamma \approx 7.5 \times 10^6$), and r_p the "classical proton radius" ($r_p \approx 1.5 \times 10^{-18}$ m). Equation (1) becomes

$$L = \gamma \left(\frac{1}{e r_p} \right) \frac{I_{\mathrm{beam}}}{\beta^*} \xi F_{\mathrm{geom}} \,, \tag{3}$$

with $\beta^* \equiv \beta_x^* = \beta_y^*$.

From (3), a linear increase with energy will be achieved naturally, thanks to the adiabatic damping of the proton beam's transverse geometric rms emittance ε, for a constant normalized emittance ($\gamma \varepsilon$).

Fortunately, since the transverse radiation damping time is short, of order 30 s (compared with 1 day at the LHC), the emittance will shrink quickly until it is balanced by an external transverse noise excitation that will need to be applied in order to maintain stable collisions at a still acceptable value of the beam-beam tune shift [38].

For the CCM, the transverse damping decrement $\lambda_d = U_0/(2E_{\mathrm{beam}} n_{\mathrm{IP}})$ is about $1.2 \times 10^{-3}/n_{\mathrm{IP}}$ (200 turns damping time), where n_{IP} designates the number of interaction points. The value of

the damping decrement is reminiscent of the e^+e^- collider LEP, where the following approximate scaling law was established [39]:

$$\xi^{\mathrm{max}} \propto \lambda_d^{0.4} \ . \tag{4}$$

From Ref. [39], we can expect a maximum tune shift ξ between 0.05 and 0.08, depending on the number of interaction points. Recent colliders, e.g., KEKB, have achieved higher tune shifts still. Conservatively assuming a maximum tune shift of 0.06 yields another factor of 10 in luminosity, compared with FCC-hh. We then arrive at an unprecedented luminosity of 2×10^{38} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which nevertheless falls short of our ideal target by a factor ~ 30. Higher tune shift or smaller IP beta functions would further boost the luminosity.

Based on the above considerations, Table I presents tentative proton-collider parameters for the CCM, and compares them with those of the planned FCC-hh and the HL-LHC. The CCM beam energy follows from $E_{\mathrm{beam}} = ceB_{\mathrm{dip}}F_{\mathrm{dip}}C/(2\pi)$, where c is the speed of light, e the electron (proton) charge, $C \approx 11,000$ km the ring circumference, $B_{\mathrm{dip}} = 20$ T the dipole field, and $F_{\mathrm{dip}} \approx 0.67$ the dipole filling factor, similar to the LHC's. Beam current and bunch spacing are kept roughly the same as for the FCC-hh and the present LHC. Assuming that the CCM will operate at $\xi = 0.06$, the rms beam size at the interaction point (IP) is 120 nm, more than two times larger than the vertical IP beam size at SuperKEKB.

Quantities of interest are the beam lifetime, the synchrotron radiation, and the power consumption. The beam lifetime is [38]

$$\tau_{\mathrm{beam}} = \frac{n_b N_b}{L n_{IP} \sigma_{\mathrm{tot}}} \ , \tag{5}$$

where the total cross section σ_{tot} can be approximated as [41]

$$\sigma_{\mathrm{tot}} \ [\mathrm{mbarn}] \approx 42.1 s^{-0.467} - 32.19 s^{-0.540} + 35.83 + 0.315 \ln^2\left(\frac{s}{34}\right) \ , \tag{6}$$

and s designates the square of the center-of-mass energy in units of GeV^2. For the collision energy of the CCM we find $\sigma_{\mathrm{tot}} \approx 283$ mbarn. With $n_{\mathrm{IP}} = 2$ IPs, the beam lifetime (5) is only about 18 minutes.

Therefore, we could require rapid top-up injection in order to maintain a constant beam current. For example, injecting every 100 seconds would keep the beam current constant to within 10%.

Parameter	CCM	FCC-hh	HL-LHC
Max. beam energy E_{beam} [TeV]	7,000	50	7
Circumference C [km]	11,000	97.8	26.7
Arc dipole magnet field B_{dip} [T]	20	16	8.3
Beta function at interaction point (IP) $\beta^*_{x,y}$ [m]	0.5	0.3	0.15
Transverse norm. rms emittance ε_n [μm]	0.2	2.2	2.5
Rms IP beam size [μm]	0.12	3.5	7
Beam current [A]	0.5	0.5	1.12
Bunches per beam n_b	1,200,000	10,400	2,760
Bunch spacing [ns]	25	25	25
Bunch population N_b [10^{11}]	1.0	1.0	2.2
Energy loss per turn U_0 [MeV]	1.7×10^7	4.67	0.007
Synchrotron radiation power P_{SR} [MW]	8.5×10^6	4.8	0.014
Critical photon energy E_{cr} [keV]	105,000	4.3	0.044
Trans. emit. damping time $\tau_{x,y}$ [h]	0.004	1.0	25.8
Beam-beam parameter / IP, ξ [10^{-3}]	60	5.4	8.6
Luminosity / IP L [10^{34} cm^{-2}s^{-1}]	$\sim$20,000	$\sim$30	5 (leveled)
Number of events/crossing (pile-up)	$\sim$10^6	$\sim$1000	135
Max. integrated lum./experiment [ab^{-1}/y]	$\sim$2000	1.0	0.35

TABLE I. Tentative proton-proton parameters for CCM, compared with FCC-hh and HL-LHC [40].

The integrated luminosity can now be estimated under assumptions similar to those adopted for proposed future colliders at CERN [40]. With 160 days scheduled for physics per year, and assuming a 70% availability of the complex, we estimate an integrated luminosity of $\sim$2000 ab^{-1} per experiment and per year.

Critical photon energies in the arcs, $(3/2)\hbar c\gamma^3/\rho$ with $\rho \approx F_{dip}C/(2\pi)$, reach the level of 100 MeV. Fortunately, in the excellent vacuum on the Moon no beam pipe would be needed. With a residual molecular or atomic density of order 10^{12}/m^3 or less [42], the vacuum quality on the Moon surface is at least 100 times better than the vacuum in the beam pipes of the LHC of 10^{15} H$_2$/m^3 [43, Chapter 12]. Therefore, the charged particles of the CCM could circulate without a dedicated vacuum system, shielding, beam pipe, and pumping system, resulting in a great cost savings. Open plane dipole magnets would allow the photons escape into the tunnel wall or into the Moon sky, depending on the scenario.

B.   Powering

A prominent concern for the CCM is identifying a power source substantial enough to both sustain the machine and compensate for energy lost due to synchrotron radiation. The energy loss per turn increases as γ^4 and decreases with circumference C (or radius) only inversely linearly, as $1/C$. It also rises linearly with beam current. Doing the algebra, and starting from 4.8 MW emitted at the FCC-hh, we arrive at the interesting number of 8,500 GW or 8.5 TW. This power must be sustained by a distributed radiofrequency system, or by an alternative acceleration mechanism. A power source at the level of 10 TW would thus appear to be required. For comparison, the total energy consumption for the entire Earth in 2019 corresponded to a source of ∼18–20 TW [44].

Fortunately, a number of possible powering scenarios for lunar habitats and other projects on the Moon have already been explored, since a major consideration of any project proposed for the Moon is power. (See, for example, Ref. [45].) Some combination of these could in principle be utilized for a CCM.

For example, NASA and the U.S. Department of Energy have begun studies of fission surface power [46–48] to be deployed for small-scale projects with minimal power needs on the Moon [49]. Since such studies target power outputs in the kW range, these are, however, unlikely to be useful for a CCM as currently envisioned.

An alternative option would be the construction of full-scale fission reactors on the Moon like those on Earth. Even if this proved possible, it is unclear whether the power output could meet the needs of a CCM. As of this writing, there are 444 operable fission power reactors used for non-military purposes in the world, with a combined power output of 394 GW [50]. Achieving tens of TW with existing fission technology will, thus, be potentially challenging.

Fusion power is in principle more promising, but there are challenges associated with fusion reactors, as well. The target power output of ITER [51] is 500 MW, from 50 MW of injected power, and, thus, a CCM would require a power output equivalent to ∼20 ITER reactors. Clearly fusion power technology will advance significantly in the next several decades, but it remains unclear when it could be harnessed to reach the 10s of TW level. As a result, alternative powering methods for the CCM should be examined.

More promising for a CCM is power from the sun. Due to its lack of atmosphere, solar power would be plentiful on the Moon. Solar power on the Moon has the additional benefit that the materials needed for manufacturing photovoltaic cells are likely already present in the rocks and dust of the Moon (as discussed in, e.g., Ref. [52]). One possible powering solution for the CCM

could, thus, be a large-scale harnessing of solar power in the form of the construction of a small patch of a Dyson sphere [53] around the sun, on or near the Moon. The total power emitted by the sun is about 400 yottawatt (4×10^{26} W) [54]. Therefore, less than a thirtieth of a part per trillion of the sun power would be needed to operate the CCM. Indeed, considering the distance between the Moon and the sun of about 150 million km, the power required corresponds to $\sim0.07\%$ of the sun power incident on the Moon surface. Assuming 100% efficient solar panels, a CCM would thus require the construction of a solar power array of $\sim6.7\times10^3$ km^2 on the lunar surface, an area slightly larger than the size of the U.S. state of Delaware. Current solar power technology achieves $\sim20\%$ efficiency on Earth, and so the total array on the Moon would need to be larger. Solar power on the Moon will also likely be complicated by the fact that radiation exposure and the high temperatures during lunar day can severely degrade and damage solar panels. NASA is currently studying ways to address these challenges [55].

The other major limitation related to using solar power in the form of a Dyson patch is that there is no part of the Moon that is constantly exposed to the sun. A solution to address both the issue with solar panel efficiency for a CCM and the issue with sun exposure would be to build a Dyson band or belt around the equator of the Moon to continuously collect sun power. Both a Dyson patch of $\sim6.7\times10^3$ km^2 and a Dyson belt of 100 km in width are shown schematically in Figure 3.

Such a Dyson belt would additionally easily provide ample power to multiple lunar projects, as well as potentially send power back to Earth. Such an idea was championed by David Criswell for many decades [57] and has been recently studied in detail by the Shimizu Corporation with the Luna Ring concept [56] and by the Japan Aerospace Exploration Agency (JAXA) for the Space Solar Power Systems (SSPS) [58].
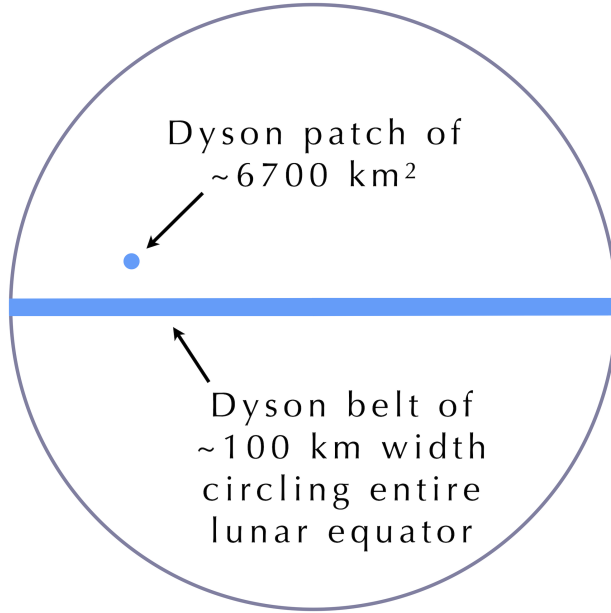
FIG. 3. Schematic demonstration of the relative size on the Moon (large gray circle) of a Dyson patch of $\sim6.7\times10^3$ km^2 (small blue dot) that could potentially collect enough solar power to provide the ~10 TW estimated to be needed by a CCM, assuming the patch could be constantly in sunlight. The patch is slightly larger than the size of the U.S. state of Delaware. Because such a spot that is constantly exposed to the sun does not exist on the Moon, also shown is the size of a Dyson belt of 100 km in width, circumnavigating the Moon around the lunar equator. Such a Dyson belt would always have a portion of the solar panels exposed to the sun. The concept is similar to the Luna Ring concept proposed by the Shimizu Corporation [56].

IV. INJECTOR

The top-up injection in time intervals of 100 s, for each ring, could be achieved with a rapid cycling "conventional" full energy booster (though achieving the implied ramp rate with 20 T magnets might be non-trivial). The full-energy booster injector must have the same size and the same peak dipole field of 20 T as the collider. The booster can be preceded by a series of lower-energy and perhaps lower field circular accelerators. Each synchrotron could increase the beam energy by about a factor of 20, as for example is done with the PS, SPS, and LHC at CERN. Field is balanced with the circumference and number of cycles required to fill the subsequent machine. As cycle times for the lower-energy machines become rather short, injecting into the first synchrotron of the chain at an energy of around 1 TeV, from a superconducting proton linac, could be an interesting option. Table II presents parameters of an example configuration sketched in Fig. 4. It is evident that the complex could be constructed in stages, and both the proton linac and the first synchrotron be initially used for other applications, while the downstream accelerators are being

constructed.

TABLE II. Parameters for a possible CCM injector chain.

Synchrotron	Circumference [km]	Max. Dipole field [T]	Cycle time [s]	Extr. / Inj. Energy
Top-Up Booster	11,000	20	50	7 PeV / 350 TeV
Pre-Booster	2,750	4	12.5	350 TeV / 17.5 TeV
First Synchrotron	550	1	2.5	17.5 TeV / 0.9 TeV
Superconducting linac	50 (length)	—	CW	0.9 TeV / $\sim$0
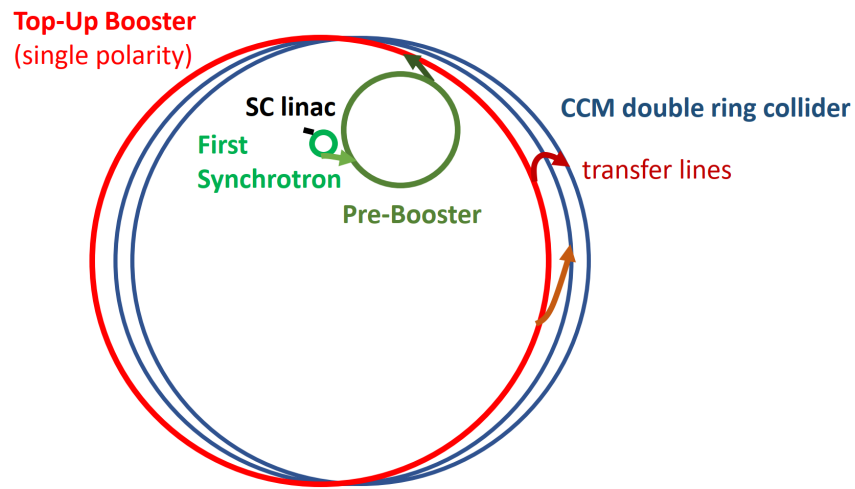
FIG. 4. Sketch of a possible CCM injector chain, with parameters as listed in Table II. The "First Synchrotron" circle (light green) is twenty times larger in circumference than the LHC.

V.   DIPOLE MAGNETS

An important consideration for the CCM is the identification and sourcing of sufficient raw materials to constitute the dipole magnets needed. In contrast to the more than 1200 dipole magnets of the LHC and the planned ∼5000 dipole magnets of the FCC, each about 14 meters long, the CCM will require ∼5.5×10^5 dipole magnets for the full, 11000-km accelerator alone, assuming a similar magnet length. (Additional magnets will be needed for the supporting accelerators in the injector complex; for simplicity we consider the CCM itself in the following.)

As discussed in Section II A, the dipole magnets of the CCM will likely be high-temperature superconductors (HTSs) targeting a magnetic field of at least ∼20 T. Two HTS approaches and technologies present themselves as possibilities for the CCM.

The first is to use HTSs based on tapes of rare-earth elements (REEs) combined with barium-copper-oxide, collectively referred to as ReBCO. (See Ref. [59] for a recent review of ReBCO technology and prospects for use in magnets for future colliders.) In practice, HTSs for accelerators are composed of both superconducting material and some amount of stabilizer, such as copper. In the case of ReBCO-based HTSs, the ReBCO layer is a small fraction of the entire material, ∼2–3%, and the REE component is ∼30–40% of the ReBCO, a comparably small fraction of the total. A sufficient quantity of usable REEs such as yttrium or gadolinium would need to be identified for the dipoles of the CCM, presenting a challenge because, as their name implies, such elements are rare. Moreover, a 1–2 μm silver layer might be needed on top of, or underneath, the ReBCO HTS material in addition to 50–100 μm copper stabilizer [60].

As a benchmark, we consider a CCM constructed of a series of 14-m dipoles, each of which consists of 2 tons of conductor total. This corresponds to ∼24 kg of REE needed per dipole, and a corresponding total amount of REE needed for the CCM of ∼1.32×10^7 kg, or ∼13200 tons.

However, hybrid magnets could be constructed from some combination of ReBCO-based HTS as an inner high-field layer and other, more conventional materials, such as Nb_3Sn, envisioned for the FCC-hh, or Nb-Ti, as for the LHC, for the outer lower-field layers. For example, a 20 T hybrid magnet consisting of three layers was considered in Ref. [61]. Under the assumption of CCM dipole magnets consisting of, e.g., 50% Nb_3Sn and 50% ReBCO, and given the benchmark above, this corresponds to ∼6600 tons of REE needed.

The total amount of all REEs on Earth is estimated to correspond to 120 million tons [62]. Sourcing REEs for the CCM on Earth and then transporting them to the Moon could, in principle, be feasible, though Earth-to-Moon material transport should likely be avoided or kept to a mini-

mum due to the cost involved. Sourcing REEs on the Moon, instead, would alleviate the need for transport. However, currently it is unclear whether REEs are plentiful enough on the Moon to be collected and used. Recent estimates suggest that lunar REEs could be abundant, but it remains to be confirmed whether they would exist in usable amounts for a CCM. (See, e.g., Ref. [63].) In principle, however, irrespective of their source, $\sim$6600 tons of REE could be collected over the decades prior to and during the construction of the CCM.

Moreover, ancillary material such as copper or silver will need to be sourced, as mentioned above. Evidence from lunar missions indicates the possible presence of silver on the Moon, as described in, e.g., Ref. [64], along with oxygen, hydrogen, sodium, and other elements, but the question as to whether such elements are present in quantities sufficient for ReBCO-based HTSs for the CCM remains open.

The second option would be to deploy magnets that utilize iron-based superconductor (IBS) [65], as is foreseen to be used for the 12–24 T magnets of the SPPC. IBSs based on iron and pnictides (typically arsenic (As) and phosphorus (P)) would alleviate the need to source thousands of tons of REE, instead requiring the sourcing of something on the order of a million tons of iron, arsenic and phosphorus. The total amount of usable metals and other elements (including iron and pnictides) on the Moon is the subject of much study, with current estimates suggesting that accessible iron could be plentiful [66, 67]. Further studies of the lunar composition will be needed to determine whether sufficient iron and pnictides for a CCM could be sourced on the Moon.

Magnet R&D for IBS technology is developing [68–71] and IBS could likely prove an appealing alternative to ReBCO-based HTS. A rough price estimate for the SPPC IBS magnets is 200k RMB (or $\sim$28k CHF as of May 2021) per meter, roughly shared between the cost of the IBS conductor and the mechanical components of the magnet [72]. Assuming the same cost, the dipole magnets of the CCM would amount to about 200 billion CHF, not including any possibly required material transport from Earth to Moon. Such cost estimates will likely be greatly affected by cooperative mining and manufacturing systems on the Moon that could serve multiple projects, including the CCM, potentially lowering the overall magnet expenses.

A more extensive study of the availability of the materials needed and construction costs for the magnets of the CCM and the supporting injector complex is left for future work.

VI.   DURATION OF CONSTRUCTION, INSTALLATION, AND COMMISSIONING

As discussed in Section II A, Scenario C — which involves excavating tunnels a few dozen to a few hundred meters under the lunar surface to avoid temperature variations, radiation damage to workers and facilities, and meteoroid strikes — likely presents the best option for the CCM. The completion of the tunneling complex needed for both the main, ∼11000-km tunnel of the CCM and the additional tunnels needed to house the other accelerators of the injection complex (as described in Section IV) — as well as the shafts from the lunar surface to the CCM tunnel, auxiliary tunnels, caverns, and alcoves — could target a seven-to-ten-year schedule. Such a tunneling schedule relies upon the construction, availability, and operation of a number of lunar tunnel boring machines (LTBMs) working simultaneously and in parallel and, thus, relies upon technology mature enough to allow for remote handling.

Construction of manufacturing centers, factories, underground buildings for support personnel, data centres, communication systems, and various infrastructure pieces, as well as construction of the dipole magnets and CCM machine components, could also proceed in parallel with tunnel excavation. As tunnel excavation would necessarily displace a large amount of rock from the lunar regolith, such resources could potentially be used in the construction of the accelerator components or detectors, and could be made available to other projects on the Moon.

Additional time — perhaps five years — will be needed for installation of the machine, commissioning, and the construction and installation of the detectors, which would bring the total time from the beginning of construction to the beginning of data-taking to about 15 years.

Prior to the beginning of CCM construction, several broader developments must occur. Reliable systems for transporting humans and some resources between the Earth and the Moon would need to be robust, regular, and affordable. Remotely-operated LTBMs must be mature, industry-quality, and available, something that may be feasible by the 2040s, depending upon several factors [73]. Detailed studies of the geological composition of the lunar regolith, as well as surveys of the lunar subsurface, to ensure the accessibility of sufficient resources to construct all components of the CCM, would need to be performed. A powering system such as the Dyson belt / Luna Ring solar powering system discussed in Section III B would need to be constructed; under the assumption that such a project would begin construction by 2035 at the soonest (according to a projection by the Shimizu Luna Ring team), it could potentially be able to provide power to other lunar projects by the 2040s or 2050s. Underground facilities for longer-term stays by researchers would need to be built and installed.

Given the multiple technological unknowns and large uncertainties associated to them, it is somewhat challenging to arrive at a concrete estimate as to the timeline for a project such as the CCM. Even under the assumption that the already excellent progress being made on these necessary preceding technologies continues apace, it is reasonable to estimate that the CCM could begin initial construction at the earliest in the 2070s or 2080s, and that the CCM might start producing data not before the beginning of the 22nd century, if not much later.

VII. OTHER CONSIDERATIONS AND OPPORTUNITIES

There are several important aspects, considerations, and opportunities associated with and presented by the CCM that are left for future work. The following is a partial list of these aspects.

- As discussed in Section III A, the beam lifetime of the CCM is already very short, at around 18 minutes. This suggests two interaction points (IPs) and, hence, two detectors. A larger number of IPs would require a more powerful injector, which is a challenging prospect, given the conditions discussed. Two IPs and two detectors suggests that the detectors both be designed in a general-purpose manner, similar to the way ATLAS and CMS were designed at the LHC. However, detector technology and hardware needed for operation under the extreme conditions of the CCM (e.g., performing tracking and triggering when the average number of events per proton bunch crossing is on the level of 10^6) would need to be developed.

- The physics program for the detectors at the CCM would likely have three pillars. The first would be a general search program for new particles and fields, including any deviations from Standard Model (SM) expectations as well as more specific, model-dependent searches for beyond the SM phenomena at an unprecedented center-of-mass proton-proton collision energy of 14 PeV. The second would be precision study of SM predictions at such high energies, including potentially heavy-ion collisions. The third pillar of the CCM research program would be informed by what is observed by preceding collider projects such as the FCC, the SPPC, or the CitS.

- The detectors of the CCM could in principle be used as cosmic-ray observatories during commissioning and non-operation.

- The prospect of thousands of CCM maintenance staff members and researchers residing permanently on the Moon is sub-optimal. Thus, a full examination of the needs of a largely remotely-operated accelerator and detector complex needs to be conducted.

- The construction of the CCM will require global collaboration similar in spirit to that of the LHC and FCC at CERN, but much larger in scale. Because of its remote location and unique circumstances, the CCM could be constructed as one component of an entire Lunar Particle and Astrophysics Research Center (LPARC). In addition to the CCM, an LPARC could feature multiple other projects and experiments such as observational astronomy, gravitational wave detectors, a very-long-baseline neutrino detector between Earth and Moon [74], dark

matter experiments, precision measurements (in low-gravity conditions), quantum computing, a quantum technology center, etc. Many such projects have been proposed over the years and all could benefit from collaboration and synergy with the CCM.

VIII.   CONCLUSIONS

The construction of a very large hadron collider around the ∼11000-km circumference of a great circle of the Moon — a Circular Collider on the Moon (CCM) — is an attractive prospect for the (next-to-)next-to-next-generation of particle physics project, a potential successor to the proposed FCC at CERN, SPPC in China, or CitS in the Gulf of Mexico. The CCM could achieve an unprecedented center-of-mass proton-proton collision energy of 14 PeV, a thousand times more energetic than the LHC, utilizing dipole magnets that optimistically reach ∼20 T.

The CCM would require ∼5.5×10^5 dipole magnets, which could be either ReBCO-based, requiring ∼7–13 k tons of rare-earth elements, or iron-based, requiring something on the order of a million tons of IBS, containing iron and pnictides. The raw materials required to construct the machine, injector complex, detectors, and facilities of the CCM can likely be sourced directly on the Moon.

Of the various scenarios for CCM construction discussed, Scenario C is the most compelling, which involves drilling shafts and excavating a nearly 11000-km tunnel — along with additional tunneling for the injector complex and auxiliary tunnels — a few dozen to a few hundred meters under the lunar surface to avoid lunary day-night temperature variations, cosmic radiation damage, and meteoroid strikes.

One plausible trajectory for the CCM would be to position it as circumnavigating the Moon approximately around the outer edge seen from the Earth, slightly displaced toward the Earth. This trajectory appears to avoid major elevation changes, and will be modified with more sophisticated tunnel-siting tools in the future.

Due to the extraordinary conditions of such a machine, including an energy loss per turn of ∼10^7 MeV and a synchrotron radiation power of 8.5 TW, a CCM powering system that relies upon abundant solar power will be needed. This could be achieved by constructing a belt of solar panels around the lunar equator at least 100 km in width, similar to what has been studied by, e.g., the Shimizu Corporation with the Luna Ring proposal.

The physics program of the CCM would be focused on exploring the unknown, searching for new physics beyond the Standard Model (BSM), as the scale of BSM physics is not concretely predictable and requires a purely exploratory mindset. The research at the CCM will be conducted by two detectors at the two interaction points, which could be built in a general-purpose manner, similar to ATLAS and CMS at the LHC. The detector design and technology required would be driven by the extreme conditions of the CCM such as an average number of proton interactions

per bunch crossing on the level of 10^6, orders of magnitude larger than the $\sim$200 at the HL-LHC.

A project such as the CCM will require global collaboration and could be one component of an entire Lunar Particle and Astrophysics Research Center (LPARC) hosting multiple experiments and projects.

Under the assumption that the already excellent progress made in the development of industry-quality lunar tunnel boring machines, transport between Earth and Moon, detailed studies of lunar geology, solar powering on the Moon, and the construction of underground facilities for humans on the Moon continues apace during the next few decades, an 11000-km, 14-PeV Circular Collider on the Moon could, optimistically, start being constructed towards the end of the 21st century, and might then begin delivering data in the first half of the 22nd century.

Such a project will be a very large step forward into the unknown, revealing unparalleled information about the universe. The CCM will be an important stepping stone toward an ultimate Planck-scale collider, with a centre-of-mass energy of $\sim$$10^{16}$ TeV, that would require a minimum size equal to a tenth of the distance from Earth to Sun [75, 76].

IX. ACKNOWLEDGMENTS

[1] **ATLAS** Collaboration, G. Aad *et al.*, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," *Phys. Lett. B* **716** (2012) 1–29, `arXiv:1207.7214 [hep-ex]`.

[2] **CMS** Collaboration, S. Chatrchyan *et al.*, "Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC," *Phys. Lett. B* **716** (2012) 30–61, `arXiv:1207.7235 [hep-ex]`.

[3] **FCC** Collaboration, A. Abada *et al.*, "FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1," *Eur. Phys. J. C* **79** no. 6, (2019) 474.

[4] **FCC** Collaboration, A. Abada *et al.*, "FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2," *Eur. Phys. J. ST* **228** no. 2, (2019) 261–623.

[5] **FCC** Collaboration, A. Abada *et al.*, "FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3," *Eur. Phys. J. ST* **228** no. 4, (2019) 755–1107.

[6] M. Ahmad *et al.*, "CEPC-SPPC Preliminary Conceptual Design Report. 1. Physics and Detector,".

[7] M. Ahmad *et al.*, "CEPC-SPPC Preliminary Conceptual Design Report. 2. Accelerator,".

[8] **CEPC Study Group** Collaboration, "CEPC Conceptual Design Report: Volume 1 - Accelerator," `arXiv:1809.00285 [physics.acc-ph]`.

[9] **CEPC Study Group** Collaboration, M. Dong *et al.*, "CEPC Conceptual Design Report: Volume 2 - Physics & Detector," `arXiv:1811.10545 [hep-ex]`.

[10] P. M. McIntyre, S. Assadi, S. Bannert, J. Breitschopf, D. Chavez, J. Gerity, J. N. Kellams, N. Pogue, and A. Sattarov, "Collider in the Sea: Vision for a 500 TeV World Laboratory," in *2nd North American Particle Accelerator Conference*, p. MOB2CO03. 2017.

[11] J. Siegrist, "NASA is going back to the moon. How could physicists collaborate?, in Remarks from

Funding Agencies to the Snowmass Process: DOE." Snowmass Community Planning Meeting, 5 October 2020, 2020.

[12] "NASA Artemis Program." `https://www.nasa.gov/artemisprogram`. Accessed: 2021-08-05.

[13] "NASA Commercial Lunar Payload Services." `https://www.nasa.gov/content/commercial-lunar-payload-services`. Accessed: 2021-08-05.

[14] F. Ruess, J. Schaenzlin, and H. Benaroya, "Structural design of a lunar habitat," *Journal of Aerospace Engineering* **19** no. 3, (2006) 133–157, `https://ascelibrary.org/doi/pdf/10.1061`. `https://ascelibrary.org/doi/abs/10.1061`.

[15] Department of the Interior, U.S. Geological Survey, "Unified Geologic Map of the Moon, 1:5M, 2020." `https://astrogeology.usgs.gov/search/map/Moon/Geology/Unified_Geologic_Map_of_the_Moon_GIS_v2`, 2020. Accessed: 2021-21-03.

[16] C. Cook, B. Goddard, P. Lebrun, J. Osborne, Y. Robert, C. Sturzaker, M. Sykes, Y. Loo, J. Brasser, and R. Trunk, "Civil Engineering Optimisation Tool for the Study of CERN's Future Circular Colliders,". `http://cds.cern.ch/record/2141838`.

[17] "Earth's Moon: Our Natural Satellite, NASA Science website." `https://solarsystem.nasa.gov/moons/earths-moon/in-depth/`. Accessed: 2021-16-03.

[18] E. Speyerer, R. Povilaitis, M. Robinson, *et al.*, "Quantifying crater production and regolith overturn on the moon with temporal imaging," *Nature* **538** (2016) 215–218. `https://www.nature.com/articles/nature19829`.

[19] "Earth's Moon Hit by Surprising Number of Meteoroids, NASA Goddard press release." `https://www.nasa.gov/press-release/goddard/2016/lro-lunar-cratering`, 2016. Accessed: 2021-16-03.

[20] M. B. Langseth and S. J. Keihm, "In-situ measurements of lunar heat flow.," in *NASA Special Publication*, vol. 370, pp. 283–293. 1977.

[21] W. Mendell, ed., *Lunar Bases and Space Activities of the 21st Century.* The Lunar and Planetary Institute, Houston, 1985. `http://ads.harvard.edu/books/lbsa/`.

[22] C. S. Allen, D. W. Cooper, J. Davila, David, C. S. Mahendra, and M. A. Tagaras, "Proposal for a lunar tunnel-boring machine." Final Report Texas A&M Univ, May, 1988.

[23] J. Rostami, C. Dreyer, and B. Blair, "Lunar Tunnel Boring Machines," in *Earth and Space 2018: Engineering for Extreme Environments*, pp. 240 – 252. 2018. `https://ascelibrary.org/doi/pdf/10.1061/9780784481899.024`.

[24] "TBMs designed for excavations on the moon, TunnelTECH, Tunnel Talk website." `https://www.tunneltalk.com/TunnelTECH-Jun2019-Designing-TBMs-for-creating-infrastructure-on-the-moon.php`, 2019. Accessed: 2021-18-03.

[25] D. M. Blair, L. Chappaz, R. Sood, C. Milbury, A. Bobet, H. J. Melosh, K. C. Howell, and A. M. Freed, "The structural stability of lunar lava tubes," *Icarus* **282** (Jan., 2017) 47–55.

[26] A. Theinat, A. Modiriasari, A. Bobet, J. Melosh, S. Dyke, J. Ramirez, A. Maghareh, and D. Gomez, "Geometry and structural stability of lunar lava tubes," in *2018 AIAA Space And Astronautics Forum And Exposition, Aiaa Space Forum, (aiaa 2018-5185)*. 2018.

[27] I. Garrick-Bethell, V. Perera, F. Nimmo, and M. Zuber, "The tidal–rotational shape of the moon and evidence for polar wander," *Nature* **512** (2014) 181–184. https://www.nature.com/articles/nature13639.

[28] R. B. Roncoli *et al.*, "Lunar constants and models." JPL Technical Document D-32296, 2005. https://ssd.jpl.nasa.gov/?lunar_doc. Accessed: 2021-18-03.

[29] M. Robinson, "Highest Point on the Moon!." Lunar Reconnaissance Orbiter Camera website, Arizona State University, 2010. http://lroc.sese.asu.edu/posts/249. Accessed: 2021-18-03.

[30] M. Robinson, "Great Wall!." Lunar Reconnaissance Orbiter Camera website, Arizona State University, 2016. http://lroc.sese.asu.edu/posts/898. Accessed: 2021-18-03.

[31] "A New Moon Rises: Lunar Topography, Smithsonian National Air and Space Museum website." https://airandspace.si.edu/exhibitions/lroc/online/topography.cfm. Accessed: 2021-14-03.

[32] M. S. Robinson, S. M. Brylow, M. Tschimmel, D. Humm, S. J. Lawrence, P. C. Thomas, B. W. Denevi, E. Bowman-Cisneros, J. Zerr, M. A. Ravine, M. A. Caplinger, F. T. Ghaemi, J. A. Schaffner, M. C. Malin, P. Mahanti, A. Bartels, J. Anderson, T. N. Tran, E. M. Eliason, A. S. McEwen, E. Turtle, B. L. Jolliff, and H. Hiesinger, "Lunar Reconnaissance Orbiter Camera (LROC) Instrument Overview," *Space Science Reviews* **150** no. 1-4, (Jan., 2010) 81–124.

[33] D. C. Humm, M. Tschimmel, S. M. Brylow, P. Mahanti, T. N. Tran, S. E. Braden, S. Wiseman, J. Danton, E. M. Eliason, and M. S. Robinson, "Flight Calibration of the LROC Narrow Angle Camera," *Space Science Reviews* **200** no. 1-4, (Apr., 2016) 431–473.

[34] P. Mahanti, D. C. Humm, M. S. Robinson, A. K. Boyd, R. Stelling, H. Sato, B. W. Denevi, S. E. Braden, E. Bowman-Cisneros, S. M. Brylow, and M. Tschimmel, "Inflight Calibration of the Lunar Reconnaissance Orbiter Camera Wide Angle Camera," *Space Science Reviews* **200** no. 1-4, (Apr., 2016) 393–430.

[35] E. J. Speyerer, R. V. Wagner, M. S. Robinson, D. C. Humm, K. Becker, J. Anderson, and P. Thomas, "In-Flight Geometric Calibration of the Lunar Reconnaissance Orbiter Camera," *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* **39B4** (Aug., 2012) 511–516.

[36] M. S. Robinson, "Lunar Reconnaissance Orbiter Camera Experimental Data Record, LRO-L-LROC-2-EDR-V1.0, NASA Planetary Data System,". https://pds.nasa.gov/ds-view/pds/viewDataset.jsp?dsid=LRO-L-LROC-2-EDR-V1.0.

[37] "Humboldtianum Basin, NASA Lunar Reconnaissance Orbiter website." https://www.nasa.gov/mission_pages/LRO/multimedia/lroimages/lola-20100604_humboldt.html, 2010. Accessed: 2021-18-03.

[38] M. Benedikt, D. Schulte, and F. Zimmermann, "Optimizing integrated luminosity of future hadron

colliders," *Phys. Rev. ST Accel. Beams* **18** (Oct, 2015) 101002.
`https://link.aps.org/doi/10.1103/PhysRevSTAB.18.101002`.

[39] R. W. Assmann and K. Cornelis, "The Beam-Beam Interaction in the Presence of Strong Radiation Damping,". `https://cds.cern.ch/record/453821`.

[40] F. Bordry, M. Benedikt, O. Bruning, J. Jowett, L. Rossi, D. Schulte, S. Stapnes, and F. Zimmermann, "Machine Parameters and Projected Luminosity Performance of Proposed Future Colliders at CERN," *arXiv: 1810.13022* (2018) .

[41] M. J. Menon and P. V. R. G. Silva, "An updated analysis on the rise of the hadronic total cross-section at the LHC energy region," *Int. J. Mod. Phys. A* **28** (2013) 1350099, `arXiv:1212.5096 [hep-ph]`.

[42] "NASA Moon Fact Sheet." `https://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html`, 2020. Accessed: 2021-25-03.

[43] O. S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock, *LHC Design Report.* CERN Yellow Reports: Monographs. CERN, Geneva, 2004. `http://cds.cern.ch/record/782076`.

[44] "Energy Production and Consumption, Our World in Data website." `https://ourworldindata.org/energy-production-consumption`. Accessed: 2021-15-05.

[45] B. Climent, O. Torroba, R. González-Cinca, N. Ramachandran, and M. D. Griffin, "Heat storage and electricity generation in the moon during the lunar night," *Acta Astronautica* **93** (2014) 352–358. `https://www.sciencedirect.com/science/article/pii/S0094576513002567`.

[46] "NASA Developing Fission Surface Power Technology press release website." `https://www.nasa.gov/home/hqnews/2008/sep/HQ_08-227_Moon_Power.html`, 2008. Accessed: 2021-11-04.

[47] "U.S. DoE, Office of Nuclear Energy, 5 Things You Need to Know about Fission Surface Power Systems website." `https://www.energy.gov/ne/articles/5-things-you-need-know-about-fission-surface-power-systems`, 2020. Accessed: 2021-11-04.

[48] "U.S. General Services Administration, Request for Information for Fission Surface Power (FSP) website." `https://beta.sam.gov/opp/b92644af4767413c9e831e633c6e2888/view`, 2020. Accessed: 2021-11-04.

[49] "A Lunar Nuclear Reactor, MIT Technology Review website." `https://www.technologyreview.com/2009/08/17/210973/a-lunar-nuclear-reactor/`, 2009. Accessed: 2021-16-03.

[50] "IAEA PRIS: Operational & Long-Term Shutdown Reactors website." `https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx`, 2021. Accessed: 2021-11-04.

[51] ITER Organization, "ITER Research Plan within the Staged Approach (Level III - Provisional Version) (ITR–18-003)," 2018. `https:`

//inis.iaea.org/search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=50056648.

[52] A. Ignatiev, A. Freundlich, and C. Horton, "Solar cell development on the surface of moon from in-situ lunar resources," in *2004 IEEE Aerospace Conference Proceedings (IEEE Cat. No.04TH8720)*, vol. 1, p. 318 Vol.1. 2004.

[53] F. J. Dyson, "Search for Artificial Stellar Sources of Infrared Radiation," *Science* **131** no. 3414, (1960) 1667–1668, https://science.sciencemag.org/content/131/3414/1667.full.pdf. https://science.sciencemag.org/content/131/3414/1667.

[54] "NASA Sun Fact Sheet." https://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html, 2020. Accessed: 2021-23-03.

[55] "NASA: Solar Power Investigation to Launch on Lunar Lander website." https://www.nasa.gov/feature/glenn/2020/solar-power-investigation-to-launch-on-lunar-lander, 2020. Accessed: 2021-11-04.

[56] "Shimizu: LUNA RING, Solar Power Generation on the Moon website." https://www.shimz.co.jp/en/topics/dream/content02/. Accessed: 2021-11-04.

[57] D. Criswell, "Lunar solar power," *Potentials, IEEE* **22** (02, 2004) 20 – 25.

[58] "JAXA: Research on the Space Solar Power Systems (SSPS)." https://www.kenkai.jaxa.jp/eng/research/ssps/ssps-index.html/. Accessed: 2021-04-05.

[59] J. van Nugteren, G. Kirby, J. Murtomäki, G. De Rijk, L. Rossi, and A. Stenvall, "Towards REBCO 20T+ dipoles for accelerators," *IEEE Trans. Appl. Supercond.* **28** no. 4, (2018) 4008509.

[60] M. Bonura and C. Senatore, "High-field thermal transport properties of rebco coated conductors," *Superconductor Science and Technology* **28** no. 2, (Dec, 2014) 025001. http://dx.doi.org/10.1088/0953-2048/28/2/025001.

[61] R. Assmann, R. Bailey, O. Brüning, O. Dominguez Sanchez, G. de Rijk, J. M. Jimenez, S. Myers, L. Rossi, L. Tavian, E. Todesco, and F. Zimmermann, "First Thoughts on a Higher-Energy LHC," tech. rep., CERN, Geneva, Aug, 2010. http://cds.cern.ch/record/1284326.

[62] "Reserves of rare earths worldwide from 2010 to 2020, Statista website." https://www.statista.com/statistics/271874/rare-earths-global-reserves/. Accessed: 2021-06-04.

[63] C. L. McLeod and M. P. S. Krekeler, "Sources of Extraterrestrial Rare Earth Elements: To the Moon and Beyond," *Resources* **6** no. 3, (2017) . https://www.mdpi.com/2079-9276/6/3/40.

[64] P. H. Schultz, B. Hermalyn, A. Colaprete, K. Ennico, M. Shirley, and W. S. Marshall, "The LCROSS Cratering Experiment," *Science* **330** no. 6003, (2010) 468–472, https://science.sciencemag.org/content/330/6003/468.full.pdf. https://science.sciencemag.org/content/330/6003/468.

[65] Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono, "Iron-based layered superconductor La[O1-xFx]FeAs (x= 0.05-0.12) with Tc = 26 K," *Journal of the American Chemical Society* **130** no. 11, (Mar., 2008) 3296–3297.

[66] I. A. Crawford, "Lunar Resources: A Review," `arXiv:1410.6865 [astro-ph.EP]`.

[67] E. Heggy, E. Palmer, T. Thompson, B. Thomson, and G. Patterson, "Bulk composition of regolith fines on lunar crater floors: Initial investigation by LRO/Mini-RF," *Earth and Planetary Science Letters* **541** (2020) 116274.
`https://www.sciencedirect.com/science/article/pii/S0012821X2030217X`.

[68] Z. Zhang, D. Wang, S. Wei, Y. Wang, C. Wang, Z. Zhang, H. Yao, X. Zhang, F. Liu, H. Liu, Y. Ma, Q. Xu, and Y. Wang, "First performance test of the iron-based superconducting racetrack coils at 10 T," *Superconductor Science and Technology* **34** no. 3, (Feb, 2021) 035021.
`https://doi.org/10.1088/1361-6668/abb11b`.

[69] D. Wang, Z. Zhang, X. Zhang, D. Jiang, C. Dong, H. Huang, W. Chen, Q. Xu, and Y. Ma, "First performance test of a 30 mm iron-based superconductor single pancake coil under a 24 T background field," *Superconductor Science and Technology* **32** no. 4, (Mar, 2019) 04LT01.
`https://doi.org/10.1088/1361-6668/ab09a4`.

[70] E. Kong, C. Wang, L. Wang, X. Wang, D. Cheng, K. Zhang, Y. Wang, Q. Peng, and Q. Xu, "Conceptual design study of iron-based superconducting dipole magnets for SPPC," *International Journal of Modern Physics A* **34** no. 13n14, (2019) 1940003,
`https://doi.org/10.1142/S0217751X19400037`. `https://doi.org/10.1142/S0217751X19400037`.

[71] J. Tang, "SPPC Study Progress," *FCC Week 2017, Berlin* .
`https://indico.cern.ch/event/556692`.

[72] Qingjin Xu, "Private communication," 2021.

[73] Jamal Rostami, "Private communication," 2021.

[74] T. L. Wilson, "An Earth-Moon Baseline Neutrino Experiment," in *Lunar and Planetary Science Conference*, vol. 23 of *Lunar and Planetary Science Conference*, p. 1537. Mar., 1992.

[75] P. Chen and R. J. Noble, "Crystal channel collider: Ultrahigh-energy and luminosity in the next century," *AIP Conf. Proc.* **398** no. 1, (1997) 273–285.

[76] F. Zimmermann, "Future colliders for particle physics —"Big and small"," *Nucl. Instrum. Meth. A* **909** (2018) 33–37, `arXiv:1801.03170 [physics.acc-ph]`.