ARTICLE

Colliding Beam Fusion Reactor

Norman Rostoker, Michl W. Binderbauer, Hendrik J. Monkhorst

Recent results with Tokamak experiments provide insights into the problem of magnetic confinement. They demonstrate how to avoid anomalous transport and thus solve the major problems of Tokamak reactors: size, the production of 14-megaelectron volt neutrons, and maintenance. An alternate confinement system, the field-reversed configuration, confines beams of protons and boron-11. For the proton–boron-11 fusion reaction, the fusion products are all charged particles for which direct conversion is feasible and neutron flux is negligible.

For more than 40 years, research toward a fusion reactor has been pursued in most of the industrialized countries of the world. During the last 30 years, most of the resources have been focused on the Tokamak, culminating in the International Thermonuclear Experimental Reactor (ITER), which will cost about $10 billion (*1*). The Tokamak has been a research facility of great value, but a reactor based on this concept has three major disadvantages.

1) Magnetic confinement in such a reactor is much less effective than expected. The phenomenon of anomalous transport leads to a large minimum size for adequate confinement. This limit implies a minimum plant size of about 10 GW.

2) The deuterium-tritium fuel yields most of its fusion energy in the form of 14-MeV neutrons, which create a great deal of radioactivity. Low-activation materials have been suggested to reduce this problem, but it is not certain that they can be developed with adequate physical properties. In addition, the 14-MeV neutrons cause radiation damage to materials. The neutron flux must be less than about 2 MW m^{-2} for the first wall to have a reasonable lifetime. Then, massive shielding is required to protect the superconducting magnets.

3) The Tokamak is toroidal. Therefore, the construction of the coils, vacuum system, and so forth make maintenance difficult and expensive.

Alternative concepts have been proposed to solve one or more of these problems. We describe the concept of a colliding beam fusion reactor (CBFR) (*2*), which in principle solves the three problems of size, neutrons, and maintenance.

Minimum Reactor Size

In a Tokamak (Fig. 1), the plasma has a strong toroidal magnetic field, produced by the coils, and a poloidal field, produced by the toroidal current in the plasma. The resultant field is helical. Particles in this field, to first approximation, follow the field lines with a small radius of gyration about the field line. The collective behavior of many particles in such a plasma results in modes of oscillation that may grow, that is, instabilities. Long-wavelength oscillations must be stable or the plasma will escape magnetic confinement in a few microseconds. There are short-wavelength oscillations that cannot be stabilized because they are due to, for example, a density gradient that is fundamental for isolation of the plasma from the material walls. Such oscillations will grow and saturate to a nonlinear limit, which leads to a spectrum of fluctuations. The fluctuations are called anomalous because they are much greater than would be expected from discrete particle effects. The fluctuations lead to anomalous transport, which is a collective effect, whereas classical transport involves two-body Coulomb scattering.

The containment time of a plasma is $\tau = R^2/2D$ (*3*), where R is the minor radius of a Tokamak plasma and D is the diffusion coefficient. The classical value is $D_c = a_i^2/\tau_{ie}$, where a_i is the ion gyroradius and τ_{ie} is the ion-electron scattering time. The Bohm diffusion coefficient attributed to short-wavelength instabilities is $D_B = (1/16)a_i^2\Omega_i$, where Ω_i is the ion gyrofrequency. For fusion conditions (particle density $n = 10^{15}$ cm^{-3}, temperature $T = 100$ keV, and magnetic field $B = 100$ kG), $D_B \approx 10^8 D_c$. If Bohm diffusion prevails, R must be very large in order to have an adequate containment time for fusion. In early experiments with toroidal confinement, Bohm diffusion was consistently observed. The fusion effort would surely have been terminated were it not for the work of Artsimovich, who proved that the containment time was $\tau \approx 100R^2/2D_B$. Recent experiments with Tokamaks suggest that $\tau = R^2/2D_c \approx 10^8 R^2/2D_B$ is possible, in which case the minimum dimension of a reactor would be reduced from meters to centimeters. These experiments involved the injection of energetic beams (about 50 keV) in order to heat the plasma in the large Tokamak experiments (*4*) at Princeton, General Atomic, and the Joint European Torus in England. In addition, the Joint European Torus was used for experiments with a burning plasma in which energetic fusion products such as tritium (about 1 MeV) were followed. In all cases, energetic ions from about 100 keV to 3 MeV slowed down and diffused classically, although the containment time of the thermal plasma was anomalously short. The energetic beam ion density was about 1% of the density and 10 to 100 times the mean energy of the ions of the thermal plasma. The physical reason for the classical behavior of the energetic ions was that such ions have a large gyroradius a_i, and they average the fluctuations so that only wavelengths larger than a_i cause anomalous transport. The large orbit ions are insensitive to the short-wavelength fluctuations that cause anomalous transport. This interpretation is supported by computer simulations (*5*). These results lead to the conjecture that if most of the ions in a plasma were energetic, classical transport (*6*) would prevail if long-wavelength modes were stable.

The problem is how to make such a

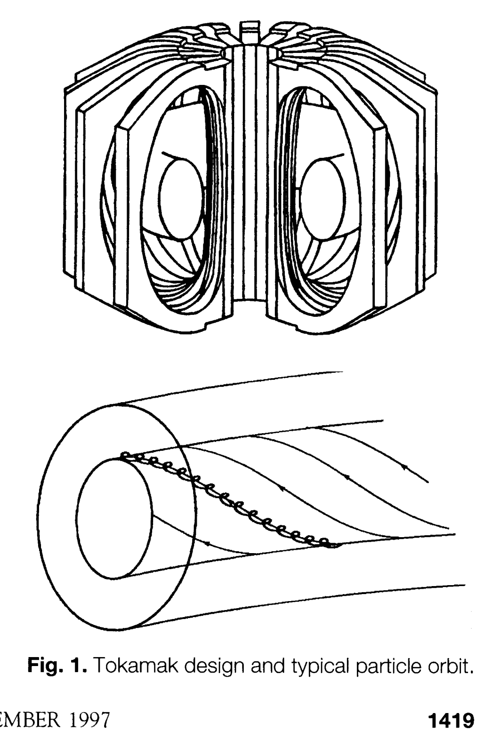

Fig. 1. Tokamak design and typical particle orbit.

N. Rostoker and M. W. Binderbauer are with the Department of Physics and Astronomy, University of California, Irvine, CA 92697–4575, USA. H. J. Monkhorst is with the Department of Physics, University of Florida, Gainesville, FL 32611–8435, USA.

plasma. The density of the injected beam in Tokamaks was increased. It was found that there is a threshold beam density above which the beam drives Alfvén modes in the background plasma; these long-wavelength modes cause anomalous beam transport (*4*). Earlier attempts to make such a plasma by injecting and trapping energetic beams also failed because of instabilities with a low threshold beam density (*7*). However, the field-reversed configuration (FRC) (Fig. 2) was successful (*8*).

Research into the FRC design started at the Naval Research Laboratories around 1960; it was also studied at Los Alamos National Laboratory (1975 to 1990), and there is a current experiment at the University of Washington. The contained particles (Fig. 2) in the FRC normally follow betatron orbits, which are typical in accelerator physics rather than plasma physics. The orbits with $v_\theta < 0$ (the diamagnetic direction) always curve toward the null surface, where the magnetic field vanishes. This result obtains for particles of different charge, mass, or energy, so that their orbits always overlap. Such overlap is important for fusion reactions to take place and would not be the case for a constant magnetic field. The drift orbits have $v_\theta > 0$ and would not be contained. They rotate in a direction opposite to the betatron orbits, and the radial magnetic field at the ends of the plasma produces a Lorentz force that expels these particles. In typical experiments at Los Alamos, the ion gyroradius was about half the plasma radius, and about half of the current was carried by energetic ions.

The FRC is surprisingly stable. Various magnetohydrodynamic (long wavelength) instabilities that had been predicted do not occur. This plasma is physically different from previously studied plasmas, which are dominated by small gyroradius particles and are described by magnetohydrodynamics (MHD). It is the starting point for the creation of a plasma with classical transport. It is already halfway there because the average gyroradius is about half the size of the plasma. Injecting and trapping beams should increase the fraction of large orbit ions because the particles are better contained. Excitation of long-wavelength modes by energetic ions is not expected, otherwise the FRC could not have been formed: There are no Alfvén waves or other MHD modes to excite.

Radioactivity

The nuclear fuels that can be used in an FRC reactor include deuterium (D) and tritium (T)

$$D + T \rightarrow \alpha\ (3.6\ \text{MeV}) + n\ (14.1\ \text{MeV}) \tag{1}$$

which produce α particles and neutrons. The reactivity $\langle \sigma v \rangle \approx 8 \times 10^{-16}\ \text{cm}^3\ \text{s}^{-1}$ has a broad peak at a temperature of about 100 keV. This is the only reaction that has been considered seriously because of its large reactivity and because the fuel has atomic number $Z = 1$, which implies the least radiation loss. However, most of the energy is produced in 14.1-MeV neutrons, which implies that induced radioactivity will be a serious problem, and conversion of the neutron energy to electric power will involve heat management, turbines, and so forth, and an efficiency of not more than 40%.

The reaction

$$D + {}^3\text{He} \rightarrow \alpha\ (3.7\ \text{MeV}) + p\ (14.7\ \text{MeV}) \tag{2}$$

producing α particles and protons, can be a considerable improvement over D-T, but the reactivity $\langle \sigma v \rangle = 2 \times 10^{-16}\ \text{cm}^3\ \text{s}^{-1}$ at 200 keV is much less, and neutrons are produced by secondary D-D reactions.

The reaction of protons with boron-11

$$p + {}^{11}\text{B} \rightarrow 3\alpha\ (8.7\ \text{MeV}) \tag{3}$$

produces no radioactivity, and radioactivity from side reactions is negligible. The reactivity has a broad peak if the energy of the proton relative to ^{11}B is 580 ± 140 keV. If the temperatures of the proton and ^{11}B beams are much less than 140 keV, the reactivity can be even greater than it is for D-T. The energy produced per reaction is half as much as that for D-T; however, direct conversion of particle energy to electric power is possible at an efficiency that is more than twice that of heat conversion. For a thermal p-^{11}B reactor, the electromagnetic radiation energy is greater than the nuclear energy produced, and a reactor that produces net energy is possible only if the conversion efficiency is nearly 100% (*9*). However, by maintaining the relative energy of the protons and ^{11}B to maximize $\langle \sigma v \rangle$, the nuclear energy produced is much greater, and recent research indicates that this process is possible in an FRC. Preliminary designs of D-T, D-^{3}He, and p-^{11}B reactors have been investigated (*10*).

Maintenance

Tokamak reactors are expensive and difficult to maintain because of their toroidal design. The confined plasma in the FRC has a toroidal geometry, but the reactor is a linear system (Fig. 3): All of the components can be mounted on rails and easily separated for repairs and maintenance. Therefore, such a reactor should prove to be much easier and less expensive to maintain than a Tokamak.

Issues and Solutions

Confinement of the energy of electrons. The electron temperature must be maintained at a high level (tens of kiloelectron volts), or the proton beam slows down too rapidly. If there is significant plasma density at the first wall, electron transport of energy becomes important, reducing the electron temperature. The beam plasma equilibria that have been studied involve a reduction in plasma density at the wall of about 10 orders of magnitude compared to the peak density (*10*). Thus, there is a broad insulation region (a vacuum) between the plasma and the wall. In addition, the plasma has a positive charge, so that electrons are electrostatically confined by electric fields of the order of 10 kV cm^{-1}. In a steady-state reactor, the fusion product plasma extends beyond the fuel plasma. However, the FRC configuration has a natural diverter surrounding the fuel plasma because the magnetic field lines beyond the fuel plasma are open (Fig. 2). Particles that reach the open field lines rapidly scatter out of the plasma region into the direct converter generators (Fig. 3).

Reactivity of the p-^{11}B reaction. In order

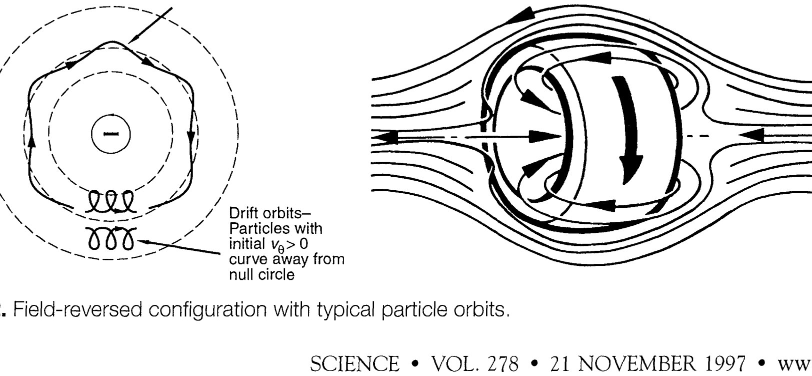

Fig. 2. Field-reversed configuration with typical particle orbits.

to exploit resonance in a steady-state reactor, it is necessary to maintain the proton and boron beams at an average energy difference of 580 keV. In addition, the temperatures of the beams must be substantially less than 140 keV. The proton beam is slowed down by the electrons and the boron beam. The boron beam, on the other hand, is speeded up by the proton beam and the electrons. In addition, the beam temperatures are increased because of scattering, most importantly the scattering of the proton beam by the boron beam. These kinetic effects drive the plasma toward thermal equilibrium. Nevertheless, it is possible to exploit the resonance.

It is important to adjust the fuel mix to minimize bremsstrahlung radiation and scattering because the atomic number Z of boron is 5. The fusion power density is proportional to $n_1 n_2 \langle \sigma v \rangle$, where n_1 is the proton density and n_2 is the boron density. The radiation is proportional to $(n_1 + Zn_2)(n_1 + Z^2 n_2)$. The scattering heats the proton beam. There is also a cooling effect because electrons are cooled by radiation and electrons cool the proton beam. This effect is well known in accelerator physics (*11*). The term most sensitive to n_2/n_1 is $\langle \sigma v \rangle$, which depends strongly on the proton beam temperature. For example if n_2/n_1 is about 0.0025 and $n_1 \approx 4 \times 10^{15}$ cm^{-3}, the temperature is $T_e \approx 20$ keV for electrons and $T_1 \approx 25$ keV for protons. Then, $\langle \sigma v \rangle \approx 8 \times 10^{-16}$ cm^3 s^{-1}, the same as the maximum reactivity for a D-T thermal reactor.

It is also necessary to maintain the average values of azimuthal beam velocities $v_\theta = v_1$ (for protons) and $v_\theta = v_2$ (for boron) so that $(1/2)m_1(v_1 - v_2)^2 = 580$ keV. In addition to the fuel plasma, it is necessary to consider the fusion product plasma, which consists of selectively confined α particles (*12*). Particles with $v_\theta < 0$ (Fig. 2) are confined and particles with $v_\theta > 0$ are released promptly, so that the confined α particles carry a current comparable to the current of the fuel plasma. In addition, the contained α particles have angular momentum. There can be a significant transfer of momentum to the protons by means of collisions, which keep them from slowing down. Fine-tuning can be accomplished by continuously injecting the fuel protons at an energy that is larger or smaller than the design energy. It is more difficult to keep the boron from speeding up as a result of collisions with the protons and α particles. This problem can be prevented by injecting low-energy protons, which couple strongly with the boron but not with the high-energy particles. This process requires only a low density of low-energy protons, so that the investment is trivial. The low-energy protons would be subject to anomalous transport, so that they would not be contained long enough to increase their energy significantly by collision processes (*13*). If we assume that v_1 and v_2 are constant, electron-ion collisions will affect the azimuthal electron velocity v_e and therefore the current, bremsstrahlung, and other parameters. In a steady state, the electron velocity will reach a compromise between v_1 and v_2, that is, $v_e = (n_1 v_1 + n_2 Z^2 v_2)/(n_1 + n_2 Z^2)$, which will be closer to v_1. This effect reduces the net current and the energy transfer from fuel protons to electrons. The net current is called the Ohkawa current (*12, 13*).

Energy extraction. Direct converters involving collector plates (*14*) and venetian blinds are not suitable for fusion product ions with energies above 1 MeV. Several types of inverse accelerators have been studied for the high-energy ions.

In the conceptual design of the D-^{3}He reactor "Artemis," a traveling-wave direct converter (*15*) for 14-MeV protons was designed with an efficiency of 75%. The device is 30 m long. Peniotron and Gyrotron converters (*16*) guide fusion product ions into a microwave cavity to generate 155-MHz microwaves; rectifying antennas produce a dc output. Efficiency as high as 90% is projected. The cavity dimensions are 1.5 m by 1.5 m by 10 m, and a magnetic field of 102 kG is involved.

We have proposed an inverse cyclotron (*13, 17*) that operates at a lower frequency (about 5 MHz) and requires a much smaller magnetic field (about 6 kG) (Fig. 3). The linear motion of fusion product ions is converted to circular motion by a magnetic cusp. The circular motion makes the device much shorter than a linear device. Collectors are also used for particles with energy less than 1 MeV.

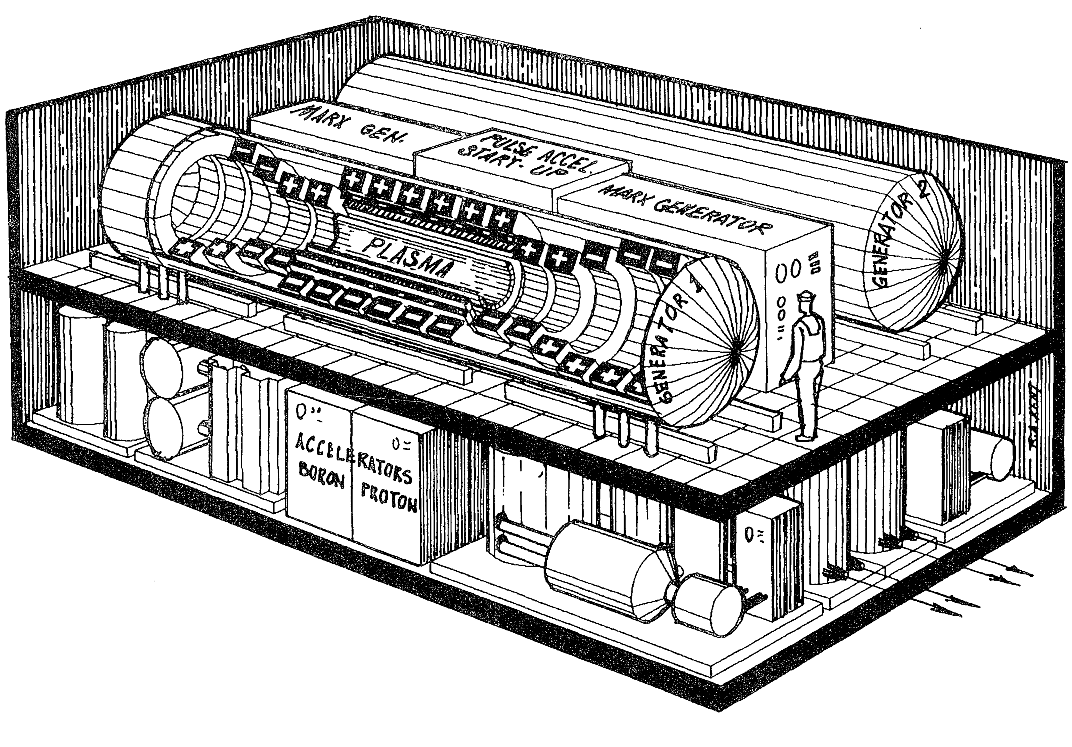

Fig. 3. Artist's conception of 100-MW beam fusion reactor. The inverse cyclotron is indicated at the ends of the generators; the size is indicated for a 50-MW output.

Energy balance. The quantity Q, the ratio of fusion power to radiation loss, is important in determining the feasibility of a reactor. Estimates (*10*) for the CBFR are $Q = 35$ for D-T, 3 for D-^{3}He, and 2.7 for p-^{11}B (*18*). Spin polarization of the fuel would (*13*) increase Q for the p-^{11}B reactor to 4.3, and a further increase may result from the nuclear quadrupole moment (*19*) of ^{11}B. The design of a 100-MW (electric) reactor (*13*) has been considered on the basis of $Q = 4.3$ by assuming a converter efficiency of 0.9 for α particles, 0.4 for radiation, and 0.7 for accelerators. The coils are assumed to be superconducting and to sustain magnetic fields of about 100 kG. The dimensions of Fig. 3 are based on these calculations.

Conclusions

The main emphasis of fusion research to date has been on the D-T Tokamak because of the large value of Q. Such a value makes the design of such a reactor much easier and much less dependent on exotic technologies. From this research has come most of the considerable body of knowledge required for fusion reactors, including the behavior of beams, which forms the basis of our present research. The purpose of this article has been to indicate another option for fusion reactor development, based on the p-^{11}B reaction. In the light of recent discoveries about the classical behavior of high-energy particles (*4*), the p-^{11}B reactor seems possible and has many engineering advantages concerning size, radioactivity, and maintenance.

REFERENCES AND NOTES

1. J. Glanz, *Science* **274**, 1600 (1996).
2. N. Rostoker *et al.*, *Phys. Rev. Lett.* **70**, 1818 (1993).
3. F. F. Chen, *Introduction to Plasma Physics and Controlled Fusion* (Plenum, New York, 1988), vol. 1, p. 190.
4. W. W. Heidbrink and G. J. Sadler, *Nucl. Fusion* **34**, 535 (1994).
5. H. Naitou, T. Kamimura, J. Dawson, *J. Phys. Soc. Jpn.* **46**, 258 (1979); G. Manfredi and R. O. Dendy, *Phys. Rev. Lett.* **76**, 4360 (1996).
6. M. W. Binderbauer and N. Rostoker, *J. Plasma Phys.* **56**, 451 (1996).
7. H. Postma *et al.*, *Phys. Rev. Lett.* **16**, 265 (1966).
8. M. Tuszewski, *Nucl. Fusion* **28**, 2033 (1988).
9. J. Dawson, *Electric Power Res. Inst. Rep. ER-429-SR* (Electric Power Research Institute, Palo Alto, CA, 1977).
10. N. Rostoker, M. Binderbauer, H. J. Monkhorst, *Comments Plasma Phys. Controlled Fusion* **18**, 1 (1997).
11. G. I. Budker *et al.*, *Part. Accel.* **7**, 197 (1976).
12. H. Berk, H. Momota, T. Tajima, *Phys. Fluids* **30**, 3548 (1987).
13. Details of the means by which to maintain the average velocities v_1 and v_2 can be found in N. Rostoker, H. Monkhorst, M. Binderbauer, Office of Naval Research reports, February, May, and August 1997 (available upon request).
14. R. W. Moir and W. L. Barr, *Nucl. Fusion* **13**, 35 (1973).
15. H. Momota *et al.*, *Fusion Technol.* **21**, 2307 (1992).
16. K. Yoshikawa, T. Noma, Y. Yamamoto, *ibid.* **19**, 870 (1991).
17. F. Bloch and C. D. Jeffries, *Phys. Rev.* **77**, 305 (1950).
18. The values used here for parameters such as density ratio and electron and ion temperatures differ from those in (*10*), but the estimate of Q is about the same.
19. L. J. Perkins *et al.*, in *Current Trends in International Fusion Research*, E. Panarella, Ed. (Plenum, New York, 1997), pp. 365–372.

20. This work was supported by the Office of Naval Research. We are indebted to G. Seaborg for his interest and advice in this research.

Impact of Lower Atmospheric Carbon Dioxide on Tropical Mountain Ecosystems

F. Alayne Street-Perrott,* Yongsong Huang,† R. Alan Perrott, Geoffrey Eglinton, Philip Barker, Leila Ben Khelifa, Douglas D. Harkness, Daniel O. Olago‡

Carbon-isotope values of bulk organic matter from high-altitude lakes on Mount Kenya and Mount Elgon, East Africa, were 10 to 14 per mil higher during glacial times than they are today. Compound-specific isotope analyses of leaf waxes and algal biomarkers show that organisms possessing CO_2-concentrating mechanisms, including C_4 grasses and freshwater algae, were primarily responsible for this large increase. Carbon limitation due to lower ambient CO_2 partial pressures had a significant impact on the distribution of forest on the tropical mountains, in addition to climate. Hence, tree line elevation should not be used to infer palaeotemperatures.

Most estimates of the cooling of tropical land areas at the last glacial maximum (LGM) are incompatible (*1*) with the much smaller decrease in sea-surface temperatures ($\leq 2°C$) estimated from microfossil assemblages in deep-sea cores by CLIMAP (*2*). For example, palaeoecological evidence for a general descent of the upper tree line by 1000 to 1700 m on the tropical high mountains at the LGM has been used to infer a cooling of 5° to 12°C, on the assumptions that temperature was the main control on the forest limit and that environmental lapse rates have remained constant through time (*3*). One possible problem with this interpretation, however, is that glacial aridity (*4*), ultraviolet-B radiation (*5*), and ambient concentrations of CO_2 (*6, 7*) may also have influenced altitudinal zonation. Here we show that changes in the partial pressure of atmospheric CO_2 (pCO_2) had a significant impact on tropical mountain ecosystems.

At the LGM, pCO_2 was reduced to a level of 190 to 200 μatm, compared with its pre-industrial level of 270 to 280 μatm (*8*). The ecophysiological effects of this large decrease in CO_2/O_2 ratio may have been exacerbated by a small increase in atmospheric O_2 content, resulting from an enhanced burial rate of organic carbon in the glacial ocean (*9*). Plants whose first product of photosynthesis is a three-carbon acid, that is, the C_3 plants, including almost all trees and most shrubs, would have been disadvantaged by increased photorespiration (*10*) and physiological drought (*11*): C_4 plants, including many tropical savanna grasses and sedges, possess a CO_2-concentrating mechanism, making them more efficient than C_3 plants at low pCO_2 with respect to the use of carbon, nitrogen, and water (*12*). Biome modeling suggests that the competitive balance shifted toward C_4 plants at all elevations in the tropics (*7*). Aquatic ecosystems would have been even more susceptible to carbon limitation than they are today because of high diffusional resistances to CO_2 uptake through water (*13*).

The $^{13}C/^{12}C$ ratio in sedimentary organic matter acts as a tracer of the carbon cycle (*14, 15*), permitting the reconstruction of past changes in the relative abundance of land plants with different metabolic path-

F. A. Street-Perrott and R. A. Perrott are in the Tropical Palaeoenvironments Research Group, Department of Geography, University of Wales Swansea, Swansea SA2 8PP, UK. Y. Huang and G. Eglinton are at the Biogeochemistry Research Centre, Department of Geology, University of Bristol, Bristol BS8 1RJ, UK. P. Barker is at the Hydrodynamics and Sedimentology Laboratory, Department of Geography, Lancaster University, Lancaster LA1 4YB, UK. L. Ben Khelifa and D. O. Olago are at the School of Geography, University of Oxford, Oxford OX1 3TB, UK. D. D. Harkness is with the Natural Environment Research Council Radiocarbon Laboratory, Scottish Enterprise Technology Park, East Kilbride, Glasgow G75 0QF, UK.

*To whom correspondence should be addressed.
†Present address: Department of Geosciences, Pennsylvania State University, University Park, PA 16802, USA.
‡Present address: Department of Geology, University of Nairobi, Post Office Box 30197, Nairobi, Kenya.