SOLUTION The radii of the two nuclei ($Z_1 = 2$ and $Z_2 = 3$) are given by Eq. 30–1: $r_{\mathrm{d}} \approx 1.5\,\mathrm{fm}$, $r_{\mathrm{t}} \approx 1.7\,\mathrm{fm}$, so $r_{\mathrm{d}} + r_{\mathrm{t}} = 3.2 \times 10^{-15}\,\mathrm{m}$. We equate the kinetic energy of the two initial particles to the potential energy when very close:

$$\begin{aligned} 2\,\mathrm{KE} &\approx \frac{1}{4\pi\epsilon_0}\frac{e^2}{(r_{\mathrm{d}} + r_{\mathrm{t}})} \\ &\approx \left(9.0 \times 10^9\,\frac{\mathrm{N\cdot m^2}}{\mathrm{C^2}}\right)\frac{(1.6 \times 10^{-19}\,\mathrm{C})^2}{(3.2 \times 10^{-15}\,\mathrm{m})(1.6 \times 10^{-19}\,\mathrm{J/eV})} \approx 0.45\,\mathrm{MeV}. \end{aligned}$$

Thus, $\mathrm{KE} \approx 0.22\,\mathrm{MeV}$, and if we ask that the average kinetic energy be this high, then from Eq. 13–8, $\frac{3}{2}kT = \overline{\mathrm{KE}}$, we have

$$T = \frac{2\overline{\mathrm{KE}}}{3k} = \frac{2(0.22\,\mathrm{MeV})(1.6 \times 10^{-13}\,\mathrm{J/MeV})}{3(1.38 \times 10^{-23}\,\mathrm{J/K})} \approx 2 \times 10^9\,\mathrm{K}.$$

NOTE More careful calculations show that the temperature required for fusion is actually about an order of magnitude less than this rough estimate, partly because it is not necessary that the *average* kinetic energy be 0.22 MeV—a small percentage with this much energy (particles in the high-energy tail of the Maxwell distribution, Fig. 13–18) would be sufficient. Reasonable estimates for a usable fusion reactor are in the range $T \gtrsim 2$ to $4 \times 10^8\,\mathrm{K}$.

It is not only a high temperature that is required for a fusion reactor. There must also be a high density of nuclei to ensure a sufficiently high collision rate. A real difficulty with controlled fusion is to contain nuclei long enough and at a high enough density for sufficient reactions to occur that a usable amount of energy is obtained. At the temperatures needed for fusion, the atoms are ionized, and the resulting collection of nuclei and electrons is referred to as a **plasma**. Ordinary materials vaporize at a few thousand degrees at best, and hence cannot be used to contain a high-temperature plasma. Two major containment techniques are *magnetic confinement* and *inertial confinement*.

In **magnetic confinement**, magnetic fields are used to try to contain the hot plasma. One possibility is a torus-shaped design, Fig. 31–12, originally called a **tokamak**.

The second method for containing the fuel for fusion is **inertial confinement**: a small pellet of deuterium and tritium is struck simultaneously from several directions by very intense laser beams (Fig. 31–13). The intense influx of energy heats and ionizes the pellet into a plasma, compressing it and heating it to temperatures at which fusion occurs. The confinement time is on the order of 10^{-11} to $10^{-9}\,\mathrm{s}$, during which time the ions do not move appreciably because of their own inertia, fusion takes place, and the pellet explodes.

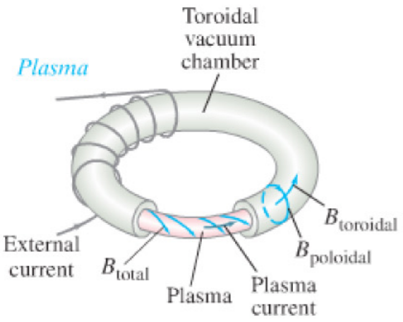

FIGURE 31–12 Tokamak configuration, showing the total $\vec{\mathbf{B}}$ field due to external current plus current in the plasma itself.

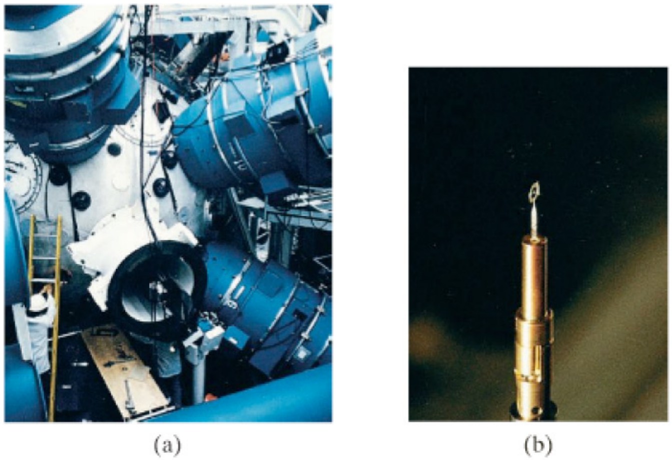

FIGURE 31–13 (a) Target chamber (5 m in diameter) of the NOVA laser at Lawrence Livermore Laboratory, into which 10 laser beams converge on a target. (b) A 1-mm-diameter DT (deuterium–tritium) target, on its support, at the center of the target chamber.