Big in Japan

Welcome to J-PARC, Japan's new accelerator facility.

Although it seems that, over the past year, all eyes have been on CERN's Large Hadron Collider (LHC) — its successful start-up in September 2008 sharply followed by a devastating failure of the machine that has kept it offline ever since — in Japan, another new accelerator has been making steady progress towards full operation, culminating in its official inauguration last month.

In fact, J-PARC is not one accelerator, but a complex of accelerators. Built jointly by the Japanese Atomic Energy Agency and the High Energy Accelerator Research Organization (KEK), J-PARC comprises a linear accelerator (LINAC), a 3 GeV synchrotron and a 50 GeV synchrotron (the Main Ring) — lower energies than expected in the LHC beams, but then J-PARC is intended for a different, complementary programme of science, especially in neutrino physics.

Since 2007, protons have been accelerated in the LINAC at J-PARC, then injected into the smaller synchrotron and accelerated to the design energy of 3 GeV. Protons from these lower-energy components of the complex are used to generate secondary beams of neutrons and muons, for studies and experiments in materials and life sciences. In December 2008, the first protons made it to the next stage: into the Main Ring, to be accelerated to the interim target energy of 30 GeV.

A further milestone was reached in January this year, when 30-GeV beams were successfully extracted from the Main Ring and steered into the 'beam dump'. That might not sound like much of an achievement, but in fact it was an essential step towards the next milestone of operation for J-PARC: in April, the first neutrino beam, created from the dumping of Main-Ring proton beams into a target, was directed from J-PARC's Tokai site (100 km north of Tokyo) to the Super-Kamiokande detector in the Kamioka mine — 295 km away.

This long-baseline experiment, named T2K (for 'Tokai to Kamioka'), is the latest to study neutrino oscillations. Japan has a proud record in neutrino physics. In 1998, Super-Kamiokande provided experimental support for neutrino oscillations, contributing to a convincing picture of this phenomenon that describes the transformation of one flavour of neutrino into another. The idea of 'oscillations' (albeit in a different form) had been suggested in the 1950s by Bruno Pontecorvo. In 1962, Japanese theorists Z. Ziro Maki, Masami Nakagawa and Shoichi Sakata devised the formalism for neutrino oscillations as we know them, based on the so-called Maki–Nakagawa–Sakata (MNS) matrix. The matrix is the link between the neutrino flavour eigenstates — electron neutrino, muon neutrino and tau neutrino — and the mass eigenstates, denoted m_1, m_2 and m_3 (crucially, the flavour eigenstates do not match the mass eigenstates). Its terms quantify the probability of oscillation, involving three 'mixing' angles (θ_{12}, θ_{23} and θ_{13}) and a phase, δ (which is non-zero only if neutrino oscillations violate CP symmetry). In fact, it's very similar to the later Cabibbo–Kobayashi–Maskawa matrix that describes the mixing between flavours of quark (and for which Makoto Kobayashi and Toshihide Maskawa took a share of the 2008 Nobel Prize in physics).

> "Another great venture in Japanese science"

Then, starting in the late 1960s, Ray Davis's experiment in the Homestake mine registered a deficit in the number of neutrinos reaching Earth from the Sun, compared with the theoretical expectation. Pontecorvo had suggested in 1967 that such an effect could occur, through oscillations. But this 'solar neutrino problem' was only properly resolved in 2001, by observations at the Sudbury Neutrino Observatory in Canada that proved that the missing fraction of electron neutrinos from the Sun had oscillated, over the vast distance to Earth, into the other flavours. Since then, a variety of experiments worldwide, using neutrinos produced by the Sun or by nuclear reactors or by cosmic rays in the Earth's atmosphere, have homed in on the values of several parameters associated with neutrino oscillation, including θ_{12} and θ_{23} and the mass difference between m_1 and m_2 (the absolute mass values are not known).

However, the third mixing angle, θ_{13}, remains unmeasured. Its value is certainly small, a few degrees at most, and could even be zero. The other unmeasured parameter, δ, is tied to CP symmetry and could have a role in explaining the matter–antimatter imbalance of the Universe. T2K is now on the trail of θ_{13} and even, after upgrades, of δ.

T2K is the most sensitive experiment so far to seek the appearance of electron neutrinos (in Super-Kamiokande) from the oscillation of muon neutrinos (produced at J-PARC). Steering J-PARC's protons into a target creates pions, which decay to muons and muon neutrinos. These neutrinos are directed towards Kamioka, but first traverse a 'near detector' at Tokai, which characterizes their energy spectrum, flux and flavour. (A major component of the near detector has an illustrious past — it's the huge magnet that was once part of the UA1 detector, used in the discovery of the W and Z bosons at CERN in the early 1980s.) The neutrinos are aimed actually slightly off target, the peak flux missing Super-Kamiokande by a few degrees. The compensation is that the energies of the off-axis neutrinos entering the 50 kilotonne Čerenkov detector are low: maximal oscillation over the 295 km baseline of the experiment is expected for neutrino energies lower than 1 GeV.

T2K, now an international collaboration including physicists from the USA, Canada, Europe and South Korea, should be joined in its quest in the next few years by other long-baseline experiments, such as one originating at Daya Bay, a Chinese nuclear reactor close to Hong Kong, and another running across the USA, from Fermilab near Chicago to Minnesota (called NOνA, and now reinstated after falling victim to budget cuts in the final days of the Bush administration). For the moment, T2K is centre-stage and set to be a star of the J-PARC show.

In a recorded message relayed at last month's inauguration, Steve Koonin, under secretary for science in the US Department of Energy, hailed J-PARC as "another great venture in Japanese science". Indeed it is. We wish success for J-PARC in its science programme — and for that other collider complex, the LHC, as it prepares to restart. ❐