Crunch time for the linear collider

Particle physicists have until the end of the year to choose between two rival designs for the International Linear Collider. **Edwin Cartlidge** reports on the tough decisions ahead

High-energy physics has always been the biggest and most expensive of the sciences. It is also among the most competitive, with accelerator laboratories in Europe, the US and, more recently, Japan competing to discover new particles and measure their properties. However, the cost of pushing back the high-energy frontier has increased beyond the means of any single country. That is why particle physicists around the world – who already collaborate to build the massive detectors for their experiments – have joined forces to drum up support for a linear accelerator that will collide beams of electrons and positrons at energies of at least 500 billion electron volts (0.5 TeV). They hope that, a decade from now, the International Linear Collider (ILC) will allow them to study in detail the exotic new particles that are expected to be revealed at the Large Hadron Collider (LHC), which is currently under construction at CERN in Switzerland.

Over the past decade physicists have developed a number of designs for a linear collider. An international collaboration centred on the DESY laboratory in Germany has been working on a design called TESLA, while researchers at the Stanford Linear Accelerator Center (SLAC) in the US and the KEK laboratory in Japan have been developing a pair of very similar proposals known as the Next Linear Collider (NLC) and the Global Linear Collider (GLC). Physicists at CERN, meanwhile, have been working on an advanced design known as CLIC.

Each design envisages the collider being about 30 km long and costing several billion dollars. With the world only able to afford one such project, particle physicists have to agree on which design to pursue, and politicians need to agree where to build it. The body co-ordinating the worldwide effort to build the ILC, the International Linear Collider Steering Committee (ILCSC), has now selected a panel of 12 experts – four each from Europe, the US and Japan – to choose its final design. This panel – known as the International Technology Recommendation Panel – has been given until the end of this year to reach a decision.

The task of the panel is made slightly easier by the fact it can discount CLIC. The CERN design is still at a relatively early stage of development and could not be built in time to complement the LHC. But choosing between the other two proposals will be tough. Last year a previous ILCSC panel concluded that both proposals are advanced and that both have their merits.

“Our decision is actually a very hard one

Eyes on the prize – physicists in the US (above), Japan and Germany each have designs for a linear collider.

because there is an embarrassment of riches,” says panel chairman Barry Barish of the California Institute of Technology. “We have two solutions, both of which would work, so the question is which is better. This is a very complicated question, involving comparisons of technological risk, cost, implementation issues, industrialization and other factors.”

Ambitious targets

Soon after it starts up in 2007, the LHC should reveal a number of new particles that are beyond the reach of today’s accelerators. These hopefully will include the Higgs boson, which is believed to endow all other particles with mass, and could also include so-called supersymmetric particles. Supersymmetry is the leading contender among theories that seek to unify the strong, weak and electromagnetic forces.

The LHC will collide protons with a centre-of-mass energy of 14 TeV. But this enormous energy comes at a price. Protons are made up of quarks and gluons, and it is these constituent particles that collide with each other, rather than the protons themselves. This means that the true collision

energy is closer to 1 TeV than 14 TeV, and that any new particles will have to be identified among the debris of a huge number of other collision products.

In contrast, the ILC will generate much cleaner collisions, as electrons are point-like. So, unlike the LHC, the new collider should be able to pin down properties of the Higgs, such as the strength of its coupling with quarks or other Higgs particles, and it should also be much better at determining the mass of supersymmetric particles. In particular, information from the ILC about the lightest supersymmetric particle could feed back into experiments at the LHC.

“In many cases each accelerator must provide crucial information for the other to maximize the sensitivity of its studies, so the combination is much more powerful than the sum of the two independent endeavours,” according to a summary of the scientific case for the linear collider published last year. This case was endorsed at a meeting of the Organization for Economic Co-operation and Development (OECD) in Paris at the end of January, where science ministers gave strong backing for the ILC.

Although the scientific case for the linear

collider is now well established, its implementation remains a challenge. Until now, most electron-positron colliders have been circular. Bunches of electrons and positrons are sent round the accelerator many times, allowing them both to be accelerated to high energies and to collide with one another on many occasions, thereby increasing the number of productive collisions or "events". However, charged particles emit synchrotron radiation when they travel in a circle, and these losses increase sharply with the energy of the particles. The losses become unsustainable for electrons and positrons at energies approaching 1 TeV, which is why the next electron-positron machine will be a linear collider.

SLAC has been operating a linear collider since 1989, but at only 3 km long it is 10 times shorter than the ILC will be. Building such a gargantuan machine poses severe technical challenges – for example how, in a single journey along the accelerator, the particles can be accelerated to the required energy and how the number of events can be maximized.

In response to this challenge, the TESLA and GLC/NLC collaborations are pursuing designs based on different kinds of cavities – devices that are positioned at intervals along the beam and that boost the energy of the electrons and positrons as they pass through (see box). The principal virtue of the TESLA technology is that it maximizes

Long road ahead – the KEK lab has developed two kinds of technology for a linear collider.

the "luminosity" – essentially the number of useful events – in the collider. At 0.5 TeV, its luminosity will be some 40% higher than that of the GLC/NLC.

But where TESLA has the advantage in luminosity, it loses out in energy reach. The ILCSC has decreed that the linear collider must reach collision energies of at least 0.5 TeV and should be upgradeable to about 1 TeV. But while the basic TESLA design should be able to reach 0.5 TeV, it is unlikely to exceed about 0.8 TeV. The Japanese and American proposal, on the other hand, is designed to reach 1 TeV and beyond.

KEK Weighing up the pros and cons

Working out the relative importance of luminosity and energy is probably the single biggest challenge facing the decision makers. "We will look at the scientific objectives of a linear collider, one by one, and try to understand how robust our ability is to answer each as a function of energy and as a function of luminosity," says Barish.

NLC project leader David Burke has no doubt about which is the most important, however. "The mission of the linear collider is to explore the energy frontier, and at this frontier, energy is the most important parameter," he says.

But Philip Burrows of Queen Mary, University of London, who is project manager on a UK programme to develop the complex systems needed to focus and collide the final beams, thinks that the crucial factor is luminosity. "My own belief is that the machine will stand or fall on the basis of its luminosity," he says. "Either technology is very capable of providing the energy."

Another key consideration is cost. In 2001 DESY released a technical-design report that put a €3.14bn price tag on the TESLA collider. Add in the detector and manpower, and the total construction cost rises to about €4bn. The core cost for the GLC, as stated in a "road map" released last year by the Japanese group, is slightly higher – €3.6bn – but since this figure includes more of the manpower costs than that of TESLA the

The technology choice – superconducting versus copper cavities

Both of the ILC's linear accelerators will consist of thousands of cavities, which produce intense electromagnetic fields oscillating at radio frequencies. The electrons or positrons "surf" along these fields, getting a kick every time they pass through a cavity. The DESY design uses superconducting cavities cooled to 2 K, whereas the US/Japanese design employs copper cavities (known as X-band technology) operating at room-temperature.

TESLA will be able to reach higher luminosities because superconducting cavities dissipate far less power, which means that more of the input power can be transferred to the beam. The lower power losses also mean that larger cavities with lower frequencies – 1.3 GHz for TESLA, compared with 11.4 GHz for the X-band – can be used to accelerate the particles, which in turn reduces the electromagnetic "wakefields" that the particles leave behind them. This is an advantage because the wakefields interact with the beam and reduce the luminosity (by increasing both the size and energy spread of the beam).

The problem with using superconducting cavities, however, is that the superconductivity is destroyed above a certain critical magnetic field strength, which

Attention to detail – physicists at DESY have produced high-gradient superconducting cavities.

limits the "accelerating gradient" of such cavities. For a collider that is about 30 km long using the niobium cavities of the TESLA design, this critical field corresponds to a collision energy of about 1 TeV. But pushing any technology to its physical limit is a challenge, which means physicists have, until recently, struggled to obtain useful gradients from superconducting cavities.

Through improvements to the niobium itself and to the way the cavities are constructed, the TESLA collaboration has shown that it is possible to reliably produce

cavities with a gradient of 23.4 MV m^{-1} , which is high enough for collision energies of 500 GeV, and have also incorporated these cavities into a short prototype accelerator. The researchers have also made a few cavities with gradients of 35 MV m^{-1} – which is needed to reach 0.8 TeV – but have so far not demonstrated that these work in the prototype.

Last year physicists working on the X-band technology produced cavities with gradients of about 60 MV m^{-1} , and they plan to trial these cavities in a test accelerator over the next few months. They say that they have effectively overcome two problems that had previously beset the X-band technology, namely how to overcome the sparking caused by surface defects in small cavities and how to distribute the radio-frequency power to all of the cavities.

In addition to X-band technology, the Japanese are also developing copper cavities that operate at a slightly lower frequency, known as C-band. A collider based on this technology would have a lower energy and a lower luminosity than one based on X-band cavities, but it would be far easier to build. This approach is being developed as a back-up in case there are problems with the X-band technology.

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total is likely to also be about €4bn. The cost of the NLC, meanwhile, is around \$6bn (about €4.7bn), although the difference between this and the other two proposals may simply reflect the different accounting systems used in the different countries.

Other factors such as reliability, outstanding R&D and scheduling must also be tossed into the mix. The TESLA collaboration says its machine would take eight years to build, whereas the Japanese and Americans have calculated that their machines would need about five years.

Also to be considered is the design of the equipment needed to generate the beams before they enter the accelerators, as well as the focusing and collision systems. The aim of the UK programme, known as the Beam Delivery System Project, which is scheduled to start work next month at a cost of about £10m, is to produce a costed engineering design for the focusing systems by 2007.

The final countdown

The International Technology Recommendation Panel held its first meeting at the end of January, where it discussed its strategy and scheduled fact-finding visits to DESY, SLAC and KEK in April and May. Barish is optimistic that the 12 strong panel will come to an agreement, and adds that the decision may come sooner than the end of the year. "I think everyone on the panel understands that it is necessary to make a clear decision if a linear collider is to move on to the next phase," he says. This next step will involve developing a proper conceptual design for the ILC, pursuing the necessary remaining R&D, and clearing up the small matter of where to build the machine.

Despite the complexity of the International Technology Recommendation Panel's task, the heads of DESY, SLAC and KEK –

Bright prospects – the TESLA design should reach higher luminosities but lower energies than the GLC/NLC.

going to build the collider. In February last year the German government agreed to pay half of the €673m needed to build a free-electron laser at DESY, which had originally been part of the TESLA project. But it refused to fund a linear collider until the international particle-physics community had agreed on a design.

The US, meanwhile, has until recently appeared lukewarm about the collider, having capped spending on NLC research in 1999. But fortunes improved in November last year when the DOE published a list of new facilities that it wants to build over the next 20 years (see *Physics World* December 2003 p5). The linear collider was ranked the highest "mid-term" priority, which, says Barish,

has already generated friction between the US and Japan. In 2001 the then head of KEK Hirotaka Sugawara, said he felt his lab had been sidelined following a decision by SLAC to collaborate with Fermilab, located near Chicago, and two other US labs. He said that the Japanese believed the machine should be built somewhere within sight of the Pacific Ocean, and objected to the prospect that it could end up in Illinois.

However, some in the physics community believe that the ILC will be built in the US. "The US is the only country that has sufficient expertise in both superconducting and room-temperature linear-collider technologies," says Burrows. Of the possible US sites, many consider Fermilab to be the most likely as it already has much of the necessary infrastructure.

But while Germany, Japan and the US compete for the prize of hosting the ILC, the top priority for most particle physicists is to ensure that a linear collider is built at all. And the first crucial step in ensuring that this happens is to make the difficult choice between the two accelerator technologies.

"Whether the linear collider gets built eventually is, of course, in the hands of governments and their funding agencies," says Greg Loew of SLAC. "But I do not believe the governments will try to reverse the physicists' choice of technology. The governments have asked the physics community to take responsibility for the selection and I think they will respect the decision, once it is made."

- tesla.desy.de
- www-project.slac.stanford.edu/nlc/home.html
- lcdev.kek.jp/
- www.ligo.caltech.edu/~donna/ITRP_Home.htm

"The decision is a very hard one because there is an embarrassment of riches."

Albrecht Wagner, Jonathan Dorfan and Yoji Totsuka – say they will respect its decision. "The members of the panel will look at all the facts and I am sure that they will make a balanced judgment," says Wagner.

But Brian Foster, head of the European Committee for Future Accelerators, believes the panel will face a tricky task. "There are some very strong-willed people on the panel who already have quite firmly held views," he says. "But Barish has the respect of the particle-physics community and I am optimistic that the panel will come to a decision."

Assuming a decision is made, politicians will then have to decide where they are

was "as good as one could have hoped for".

The Japanese government has so far not made any statement regarding the linear collider. Sachio Komamiya of Tokyo University says that his government recognizes the linear-collider research being carried out by Japanese scientists and that it backed the recent OECD statement. But he says it cannot commit itself to the ILC because it is funding a \$1.5bn accelerator complex known as J-PARC until 2007. He adds that it is unclear how the government's desire to host the \$5bn ITER fusion project will affect Japan's potential to host the ILC.

The issue of where to build the collider