PROCEEDINGS OF SCIENCE

The International Linear Collider: Physics Case and Status

Thomas Schörner-Sadenius*
Deutsches Elektronen-Synchrotron (DESY), Notkestr. 85, D-22607 Hamburg, Germany
E-mail: thomas.schoerner@desy.de

The case for a linear high-energy electron–positron collider, and in particular for the International Linear Collider (ILC), is reviewed, and an overview of the ILC machine and the foreseen detectors is given. Finally, a possible timeline for the decision process towards the ILC and for the realisation of the project in Japan is sketched.

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1. The case for a linear high-energy electron–positron collider

Particle physics faces well-known fundamental challenges. Among them are the discovery of the nature of dark matter, the explanation of the matter-antimatter asymmetry in the universe, the unveiling of the structure of the vacuum and of the nature of electroweak symmetry breaking, the question of neutrino masses or the so-called hierarchy problem. Numerous of these challenges can be addressed — and hopefully solved — by studying in great detail, and thus with highest possible precision and at sufficiently high energy, those elementary particles that promise the closest connection to physics "beyond the standard model" — the top quark and the Higgs boson of about 125 GeV mass — and by direct and indirect searches for new particles and phenomena at the highest accessible scales.

The requirements on the machine to perform the necessary tasks can easily be sketched: The required precision calls for a high-luminosity lepton collider; a centre-of-mass energy well above the thresholds for top quark pair production and for studies of the top-Yukawa coupling and the Higgs self-coupling is essential; and the possibility to extend the machines to even higher energies required for searches for new heavy particles is highly desirable, as is the possibility to have polarised lepton beams. Furthermore, the overall price-tag of such a machine, its estimated power consumption and the timescale on which it might be realised — given the political will — are important factors to be considered. Taken together, these requirements, in the minds of many elementary particle physicists, point towards a linear electron-positron collider of at least 500 GeV centre-of-mass energy with the technical possibility for further extension into the TeV range. The technically most mature proposal for such a machine is that of the International Linear Collider (ILC). Figure 1 shows a comparison of the achievable luminosity versus centre-of-mass energies of various proposals for future electron-positron colliders.

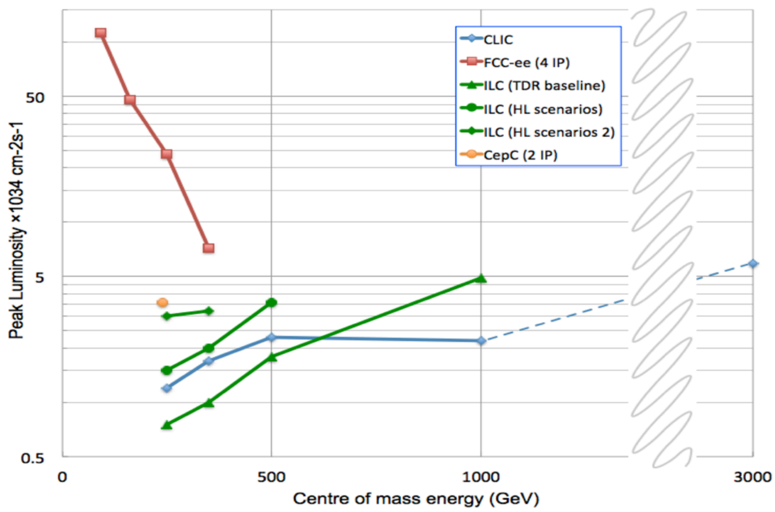

Figure 1: Comparison of the luminosities and centre-of-mass energies of various proposed electron-positron colliders. Source: N. Walker.

2. The International Linear Collider

The ILC is a proposed linear electron-positron collider with a centre-of-mass energy of between 250 and 1000 GeV and a luminosity, at 500 GeV, of at least 1.8×10^{34} cm^{-2}s^{-1}. The machine is based on superconducting radio-frequency niobium cavities operating at 1.3 GHz (cooled by 2 K helium) and has a length, at 500 (250) GeV, of about 30 (20) km. For the 500 GeV machine, 16000 cavities with Q factors of better than 10^{10} and an average performance of 35 MV/m will be organised into 1800 cryo-modules. The technical design report of the ILC was published in 2013 [1]. Figure 2 shows the baseline layout of the 500 GeV machine for which a power consumption of 163 MW was estimated.

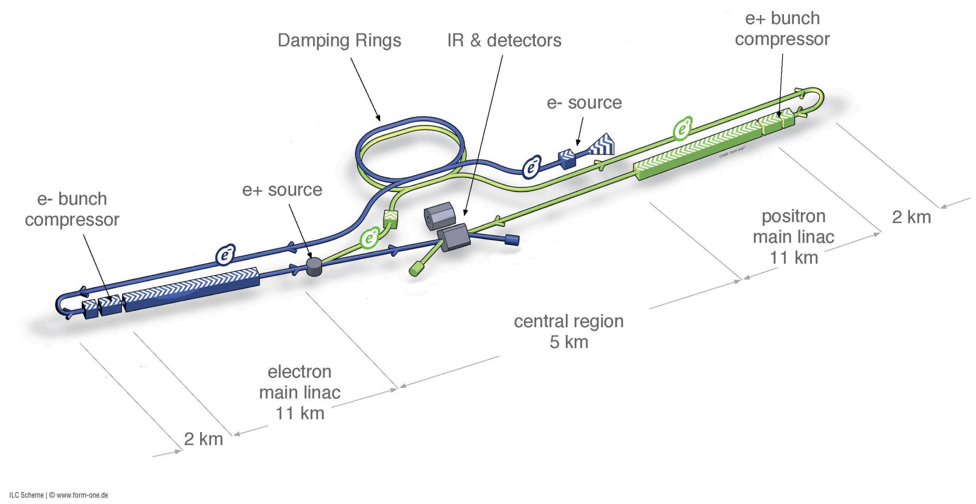

Figure 2: ILC baseline design. Source: KEK.

The physics case for the ILC is straightforward and consists of the three pillars Higgs physics, top-quark physics, and searches for new physics.

- At 500 GeV centre-of-mass energy, all Higgs couplings can be measured with percent precision, in a simple counting experiment and in a model-independent way. And even at 250 GeV, where the WW fusion process does not yet contribute significantly to Higgs production (see Fig. 3), it is possible to extract the Higgs couplings at superior precision, using an effective field theory approach [3]. The approach provides sufficient handle to discriminate the standard model Higgs against numerous other models that are invisible even at the high-luminosity LHC (HL-LHC).

- An energy sufficiently high to scan the top quark pair production threshold at around 350 GeV would allow the top mass to be measured with a precision of 17 MeV (0.01%) and the width with about 26 MeV (2%). With such measurements, also the important question of the stability of the vacuum could be answered [4]. Also the top electroweak couplings could be extracted with superior precision in the few-percent range, see Fig. 4 [5].

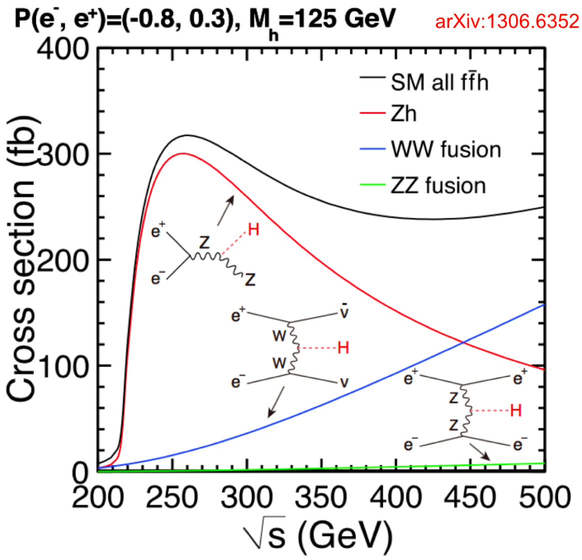

Figure 3: Higgs reach at the ILC [2].

- Finally, the direct and indirect reach of the machine for new physics is very promising. The ILC will be able to probe scales of up 20 TeV, and up to 80 TeV in extreme scenarios [6].

In summary, the ILC, especially when taken together with the results from the LHC and the HL-LHC, would provide the best currently possible outlook on physics beyond the standard model.

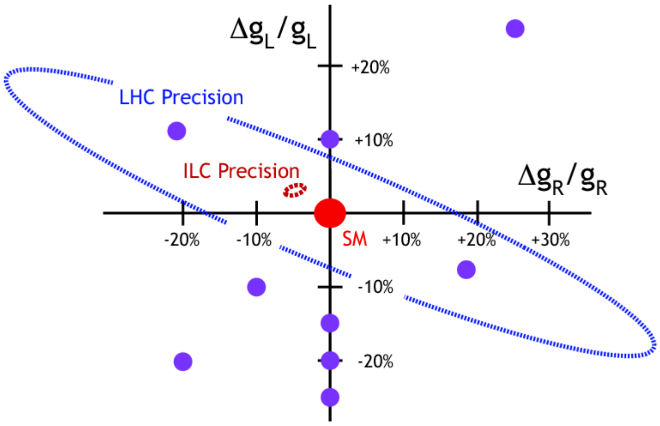

Figure 4: Projected precision for the extraction of the top coupling to the Z boson at the LHC and the ILC [5].

However, there are formidable challenges to be solved. To mention one example: In order to achieve the desired luminosity of 1.8×10^{34} cm^{-2}s^{-1}, extremely small beam sizes have to be realised at the interaction point. The so-called nano-beam scheme requires beams with about 6 nm width in the vertical direction. Further significant accelerator problems to be solved are the positron source and the beam dump. However, these issues are being worked on and are no showstoppers for the ILC project as a whole. All in all, confidence in the machine design is high, and the justification for this confidence can be seen in Hamburg, at DESY: the European XFEL.

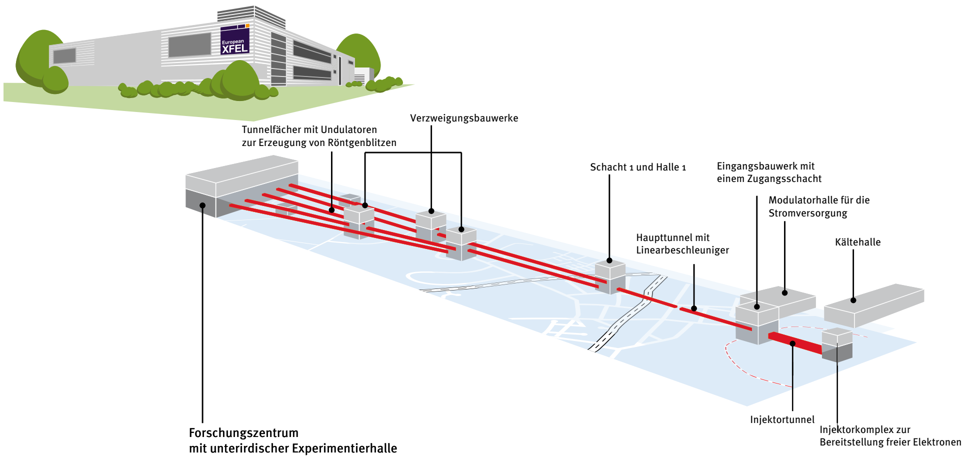

Figure 5: Overview of the European XFEL facility. Source: Britta von Heintze/Welt der Physik.

3. The European XFEL

The European XFEL [7] is a 3.4 km long accelerator based on the superconducting radio-frequency technology developed for the ILC. With a main linac length of 1.7 km and a design energy of 17.5 GeV for its electron beam, which is in later stages of the machine used to generate X-ray laser light, the European XFEL can be considered a prototype of the ILC. The European XFEL has been under construction since early 2009; routine user operation began in September 2017. Figure 5 shows an overview of the machine.

The European XFEL houses 800 niobium cavities in 100 cryo-modules, with an average accelerating gradient of 23.6 MV/m. For the production of the cavities, European industries have been involved, and the experience with these industries (learning curve, quality control and assurance) are promising, again raising confidence that also for the ILC cavity production can successfully be organised via industries. Figure 6 shows high-voltage test results of the European XFEL cavities and cryo-modules. It can be seen that European XFEL specifications can easily be achieved; additional test results also after re-treatment of cavities shows that extrapolation to ILC requirements will be possible.

4. Detectors for ILC

The current planning for the ILC foresees two detectors, for which detailed concepts have been developed over the past years: ILD and SiD (see Fig. 7) will be operated alternately in a "push-pull" configuration. Both detectors feature precision tracking components: a time projection chamber together with intermediate silicon tracking and vertexing layers in ILD (200 space points

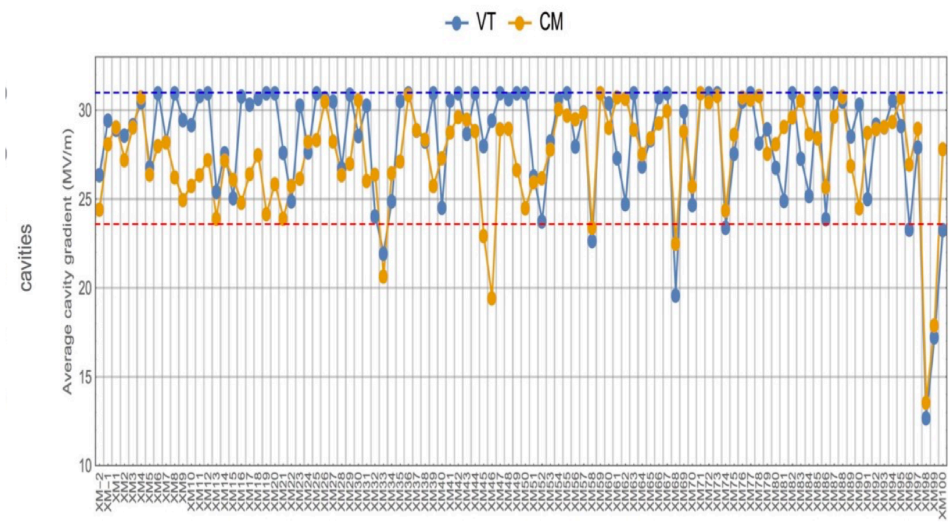

Figure 6: High-voltage test results of European XFEL cavities ("VT") and cryo-modules ("CM").

per track at 60–100 μm resolution and with dE/dx capability), and a silicon-only vertexing and tracking detector for SiD. In all cases, a minimum material budget is mandatory. Both ILD and SiD will have electromagnetic and hadronic calorimetry with particle-flow abilities [8], and they will be operated triggerlessly. A possible solution for the electromagnetic calorimeters is a silicon-tungsten sampling solution with 5×5 mm^2 cell size and a highly integrated readout, while for the hadronic calorimeters, semi-digital and analogue solutions are under discussion. Of particular importance are also the forward detectors which are developed in a separate FCAL collaboration [9].

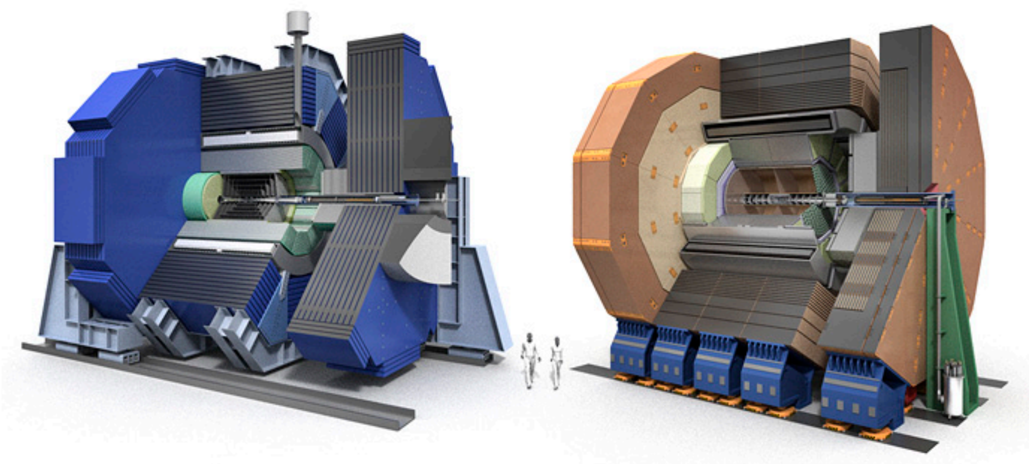

Figure 7: The two detectors currently foreseen for the ILC: SiD (left) and ILD (right). Source: KEK.

5. The decision process towards the ILC

In the fall of 2012, the Japanese high-energy physics community expressed its interest to host the ILC. Then, 2013 was a very busy year: The ILC technical design report was published, the European strategy for particle physics supported the ILC project, and a site in the Kitakami mountain region in the Iwate prefecture was suggested by the Japanese community as a place for realising the ILC in Japan. Furthermore, the Japanese ministry for (among other things) education and research, MEXT, started a detailed evaluation process of the ILC project, setting up an "ILC Advisory Panel" in May 2014 and working groups on the physics case, the validation of the technical design report, and the human resources situation. Very early in this process it became apparent that the price tag of the project was considered too high and that cost reduction was required. Figure 8 from the technical design report shows the distribution of costs of the ILC project over various categories.

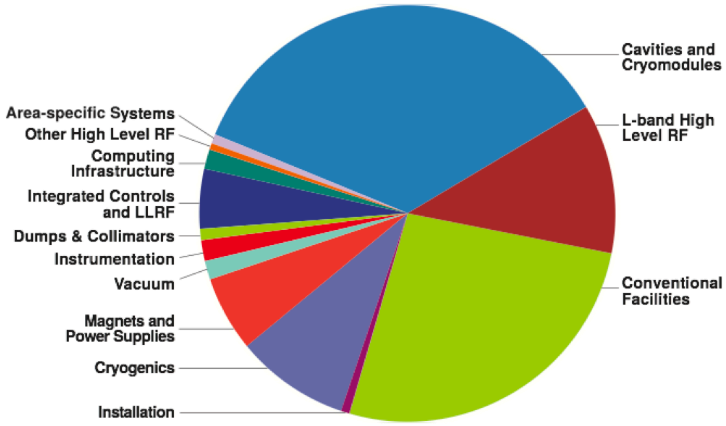

Figure 8: Distribution of ILC accelerator costs over various categories according to the technical design report.

As the most significant measure towards cost reduction (besides e.g. increasing the accelerating gradient of niobium cavities by nitrogen infusion etc.), a staging of the project was brought into play: Instead of starting right away with a 500 GeV, 30 km machine, the new plan now foresees initial data taking periods with a 250 GeV machine, probably in a tunnel that is also adapted to the lower energy (20 km) and can be extended later on. The costs for this reduced 250 GeV machine would amount to 6.35-7.03 billion USD [10] (excluding detectors, land purchase, preparation phase costs, operation costs). Figure 9 shows a possible running scenario with runs at 250, 350 and 500 GeV that would allow all ILC physics goals to be reached.

MEXT's ILC Advisory Panel finally came up with a report on the ILC [10], on which the Science Council of Japan commented in late 2018 [11] (to which again the community and also the Japanese High Energy Accelerator Research Laboratory KEK reacted [12]). This statement of the Science Council together with other deliberations and information will finally form the basis on which the Japanese government will build its decision for or against the realisation of the ILC. This decision was, in principle, expected before the deadline for the input to the update process for the European strategy for particle physics (December 2018). It is now expected for early March 2019,

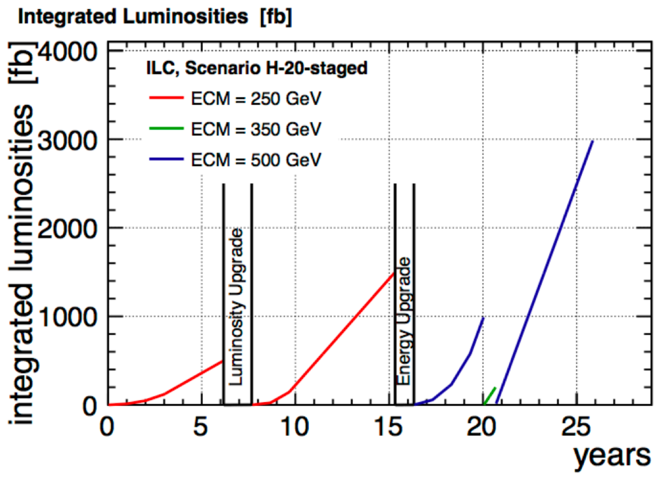

Figure 9: Possible ILC running scenario with a starting energy of 250 GeV and subsequent energy upgrades [3].

when the relevant bodies of global particle physics (ICFA, Linear Collider Board) will convene again to discuss future directions and the situation of particle physics at the advent of the update process of the European strategy.

In parallel, discussions on possible international support for the ILC in Japan between Japan and other countries (in particular the US, France, and Germany) were conducted on the parliamentary, ministerial and expert level — it is clear that international consensus and a sharing of the significant cost are mandatory for the success of a large project like the ILC.

Assuming a positive decision to host the ILC from the Japanese government, and assuming that the ILC is ranked among the high-priority items on the European strategy to be published in May 2020, then international negotiations and the detailed planning of the project might begin. For these preparatory steps, a period of at least four years is foreseen, after which construction of the accelerator and, in parallel, of the detectors could begin. First physics might then, optimistically, be expected for the mid-2030s — just in time to replace the HL-LHC as an international flagship of particle physics.

6. Summary and conclusions

At the time of writing this report, the particle physics community is eagerly waiting for a statement from the Japanese government on the realisation of the ILC in Japan. This statement is expected latest by early March 2019.

The ILC is the best-suited concept for a machine addressing the pressing questions of the field of particle physics. It is technically mature, its design, costing and human ressources situation have been scrutinised in great detail, and even discussions about potential (in-kind) contributions from other world regions have started [13]. Also studies for a convenient site in Japan for the machine have gone a long way.

However, to some extent the choice of a given machine is a question of what one wants in detail, of where one expects new physics to show up soonest (e.g. directly at high scales or rather in ultra-precise measurements at the Z pole?) — and of when one wants to start a new project (rather now, or maybe only in a number of years from now, when potentially a novel accelerator technology has seen its breakthrough?).

In the end, the realisation of the ILC or of any other machine will require a global consensus among politicians and funding agencies. In this respect, 2019 will be a very exciting year.

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