

LINEAR COLLIDER STUDIES

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Abstract

Two major Linear Collider (LC) accelerator studies are currently on-going. The International Linear Collider (ILC) based on Super Conducting RF (SCRF) technology aims for implementation during the next 10-15 years strongly motivated by the recent Higgs discovery, while the Compact Linear Collider (CLIC), based on X-band normal conducting accelerator structures and a drive beam to provide optimised RF power to the main beams, has a post-LHC time perspective and aims towards energy frontier physics at higher energies. While the basic RF technologies are different leading to different optimisation of bunch lengths, charges and repetitions rates, many key technical challenges are in common. Several major parts of the designs, as sources, damping rings, beam delivery and final focus systems to mention a few, are covered by common or connected studies. The physics potential and main detector issues, as well as possible implementation stages are being studied in parallel for both machines. A summary of recent progress and status of a selected set of studies are given below.

ILC AND CLIC PROJECT OVERVIEW

The key parameters for ILC and CLIC at their design energies are shown in table 1. The ILC design [2] is compatible with later upgrades to 1 TeV, while a 3 TeV CLIC will be built with initial stages at ~500 GeV and ~1.5 TeV [3]. The exact energy stages are in the process of being re-evaluated and changed taking into account the Higgs energy scale now known and other developments.

Table 1: ILC and CLIC main parameters

Parameter	ILC 500 GeV	CLIC 3 TeV
Luminosity [$\text{cm}^{-2} \text{s}^{-1}$]	1.8×10^{34}	5.9×10^{34} *
Accelerator length [km]	31	48.3
Acc. gradient loaded [MV/m]	31.5	100
Bunch charge [10^9 e]	20	3.72
Bunch separation [ns]	554	0.5
Number of bunches	1312	312
Repetition rate [Hz]	5	50
H./V. norm. emittance [$10^{-6}/10^{-9}$]	10 / 35	0.66 / 20
H./V. IP beam size [nm]	474 / 5.9	40 / 1

* Total, luminosity within 1% of peak: 58% and 32%

Physics Motivation for Future LCs

Future LCs can deliver high luminosity ($\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) e+e- collisions from ~100 GeV to 3 TeV. The natural first stage, at or above the 350 GeV top-pair-production threshold, gives access to precision Higgs physics through the Higgs-strahlung and WW-fusion production processes, providing absolute values of Higgs couplings to both fermions and bosons. This stage also addresses precision top physics [3]. ILC is technically mature and can provide access to very precise and model independent measurements in these areas relatively quickly. The potential of providing unique information about New Physics through such measurements [2], overlapping with and complementing LHC high luminosity running on a similar timescale, provides a strong motivation for ILC.

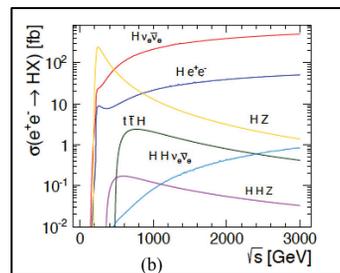
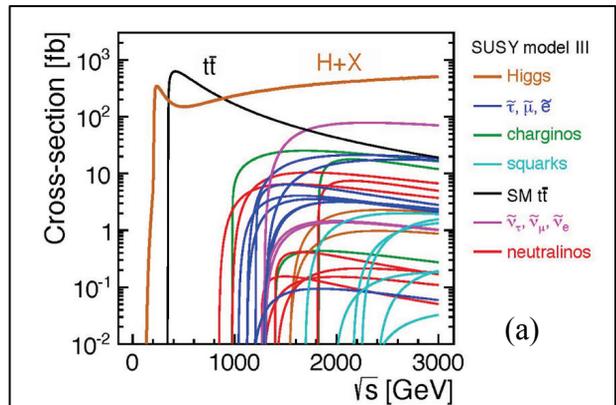


Figure 1: a) Cross-section for various physics processes at a LC as function of CoM energy. The Higgs and top studies are known opportunities, while various type of Beyond the Standard Model

processes (a SUSY model in this example) are currently still speculations; b) Various types of Higgs production processes become available as the CoM energy increases, showing that slightly above 500 GeV new channels can provide important additional information.

Further LC stages open the energy frontier in earnest, potentially allowing for the discovery and direct access to New Physics phenomena as illustrated in figure 1. This stage also gives access to additional Higgs properties, such as the top-Yukawa coupling, the Higgs potential and rare Higgs decay branching ratios. LC energies of 3 TeV as aimed for by CLIC enlarges the physics potential even further, covering the complete scope for precision

Standard Model physics, direct searches for pair-production of new particles up to 1.5 TeV mass and optimal sensitivity to New Physics at much higher mass-scales through precision measurements. Further LHC running at 13-14 GeV will be important to fully evaluate the potential of a LC at these higher energies [3].

The ILC Accelerator Concept

The overall ILC system design has been chosen to realize the physics requirements with CoM energy of 500 GeV and a peak luminosity of $\sim 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Figure 2 from the 2013 ILC Technical Design Report (TDR) [2] shows a schematic view of the overall layout of the ILC, indicating the location of the major sub-systems:

- a polarized electron source based on a photocathode DC gun;
- an undulator-based positron source, driven by the 150 GeV main electron beam;
- 5 GeV electron and positron damping rings (DR) with a circumference of 6.7 km, housed in a common tunnel at the center of the ILC complex;
- beam transport from the damping rings to the main linacs, followed by a two-stage bunch compressor system prior to injection into the main linac;
- two 11 km long main linacs, utilizing 1.3 GHz SCRF cavities, operating at an average gradient of 31.5 MV/m, with a pulse length of 1.6 ms;
- a 4.5 km long beam delivery system, which brings the two beams into collision with a 14 mrad crossing angle, at a single interaction point which can be shared by two detectors.

The total footprint is ~ 31 km. To upgrade the machine to 1 TeV, the linacs and the beam transport lines from the damping rings would be extended by another ~ 11 km each.

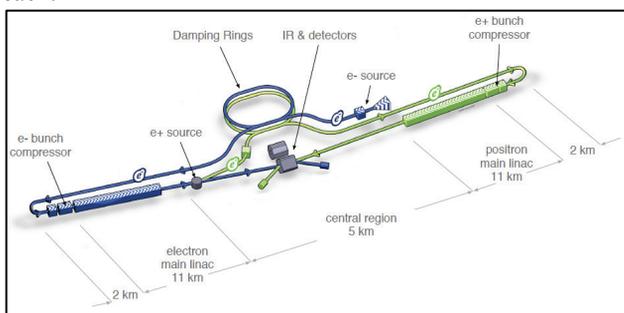


Figure 2: Schematic layout of the ILC, indicating all the major subsystems (not to scale).

The CLIC Accelerator Concept

The Compact Linear Collider (CLIC) project explores the possibility of constructing a future multi-TeV linear electron-positron collider for high energy frontier physics post LHC. The CLIC-concept is based on high gradient normal conducting X-band (12 GHz) accelerating structures. The RF power for the acceleration of the

colliding beams is produced by a two beam acceleration scheme, where power is extracted from a high current drive beam that runs parallel with the main linac. Figure 3 shows a schematic view of the CLIC complex, showing the initial 1 GHz drive beam at 2.4 GeV being compressed in a delay loop and combiner rings to intense pulses being distributed along the main linac, and the main beams being generated in central complexes (e- and e+ sources, injectors and damping rings) and then transported to and injected at the end of the two-beam linac arms. High luminosities are achieved by very small beam emittances, which are generated in the injector complex and maintained during transport to the interaction point. A 20 mrad crossing angle is foreseen. The total footprint at 3 TeV is ~ 48 km, while a 500 GeV machine would be ~ 11 -13 km depending on the gradient chosen for the initial stage. The CLIC Conceptual Design Report (CDR) was released in 2012.

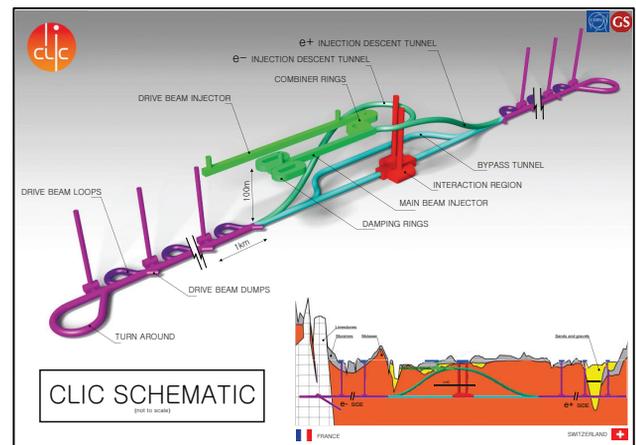


Figure 3: Schematic layout of CLIC, indicating all the major subsystems (not to scale).

RECENT PROGRESS

There are numerous on-going technical studies for the ILC and CLIC, and several of them are combined studies. A few examples are described in the following, either specific for ILC or CLIC, or with a common focus.

ILC TDR and CLIC CDR

The ILC TDR [2] is very complete and describes a mature machine design. In particular the SCRF technology is well established industrially and in all regions. Current ILC studies are related to a site specific design and planning for a possible implementation in Japan, in parallel with several technical studies focusing on areas where further gain can be made in costs, simplicity and robustness. Examples are the positron source, cavity integration (tuner, coupler), final focus magnets and the cryogenics system.

The feasibility of the CLIC accelerator has been demonstrated through prototyping, simulations and large-scale tests, as described in the CDR [3]. In particular, the two-beam acceleration at gradients exceeding 100 MV/m has been demonstrated in the CLIC test facility CTF3.

The key on-going studies cover accelerator parameter optimization, X-band systems, technical component development of part critical for cost, power or performance reasons, alignment and stability including a number of system performance studies in test-facilities around the world.

RF Studies

In the area of SCRF systems one example of recent progress is the build-up a high performance string at KEK (STF: Superconducting Test Facility). FLASH at DESY (operational machine) and ASTA at FNAL are other existing strings in Europe and the US. The purpose of the KEK-STF is to establish super-conducting accelerator technology for ILC. Another aim is the MEXT Quantum Beam project for high brightness X-ray generation by inverse laser Compton scattering. Figure 4 from [4] shows the results of vertical tests conducted for evaluating the performance of the 9-cell cavities KEK-12 through KEK-22 in the Quantum Beam Project and STF-2, processed in different ways. The KEK-12, KEK-13, KEK-17, and KEK-21 cavities met the ILC specification of accelerating gradient only upon application of the electro-polishing process in one or two vertical tests. However, all other cavities, except KEK-16, attained an accelerating gradient higher than 35 MV/m after application of a local mechanical grinding method. Details can be found in [4].

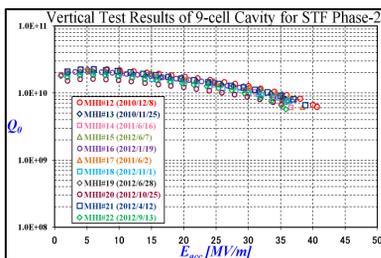


Figure 4. Best Q_0 vs. E_{acc} curves obtained in performance tests of KEK-12 through KEK-22 [4].

The CLIC normal conducting structure design has been carefully optimized using empirical constraints to achieve a gradient of 100 MV/m. The main limitation arises from so-called breakdowns, i.e. sparks that can occur in the structure during the RF pulse, which can give transverse kicks to the beam. This should happen only in 1% of the beam pulses at the target gradient of 100 MV/m, which results in a target rate of 3×10^{-7} events/(m×pulse). Such structures with the required performance are being consistently produced [3] but the statistic is limited, mainly due to the time needed to condition and perform high power tests of the structures. Two new X-band test-facilities have become operational at CERN the last years and one more is underway increasing the overall test-capacity by a factor three. In parallel complete CLIC modules are built for laboratory (mechanical) and beam

testing (active) in the CLIC test facility at CERN. These modules are 2 long and hold 8 accelerator structures and 4 power extraction units for the drivebeam. The CTF3 module is currently being installed and will be a central part of the future CTF3 programme (see Fig.5).

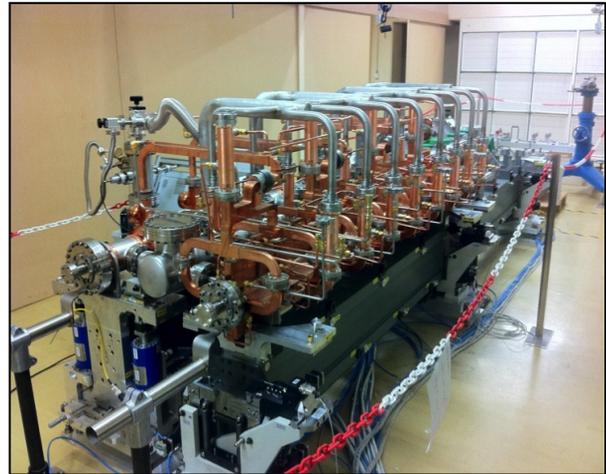


Figure 5: A first complete CLIC mechanical module for mechanical and thermal tests.

LC Beams – Experimental Verification

The challenge of colliding nanometre-sized beams at the interaction point involves three connected challenges: creating small emittance beams; preserving the emittance during transport, acceleration and beam delivery; and focusing the beams to nanometre sizes before collisions.

The small emittance beams have many common features with the beams in 3rd generation light sources, and the studies of creation of such beams are closely linked with such facilities. Specific studies involve positron production, damping times, electron cloud effects and extracting of low emittance beams.

In ATF (Accelerator Test Facility) at KEK, studies of the final focus system have been performed using small emittance beams extracted from the damping ring. The project is called ATF2. The ATF2 beam line at 1.3 GeV is designed as a prototype of the final focus system of ILC, with basically the same optics, similar beam energy spread, natural chromaticity and tolerances on magnetic field errors. Its design, construction and operation have been performed as an international collaboration. Also CLIC specific studies and hardware are being introduced.

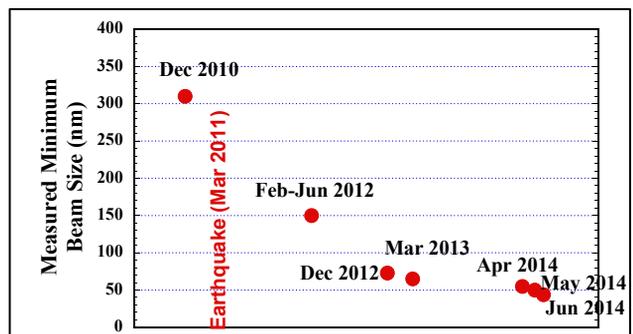


Figure 6: Progress of the ATF2 beam size optimisation.

The primary goals for ATF2 have been to achieve a 37 nm vertical beam size at the IP corresponding to the ILC requirements, stabilise it at the nanometre level, and then maintain the beam size and stability over a period of time. In May-June 2014, ATF2 achieved a vertical beam size of 44 nm, close to its initial goal [5]. The R&D towards successful completion of the goals will continue. Figure 6 shows the progress of the ATF2 beam size achievements.

The performance of future linear colliders will depend critically on beam-based alignment and feedback systems. The preservation of low emittance beams is notoriously difficult to demonstrate experimentally but very significant progress has been made recently. In ILC and CLIC it is planned to perform dispersion-free steering (DSF) in the main linacs. To this end the beams are accelerated with different gradients to evaluate the dispersion. The steering is performed by minimizing the average offset of the different beams in the beam position monitors and, at the same time, the difference between the beam trajectories. Similarly wakefield-field free trajectories can be evaluated by varying the bunch-charge (wakefield-free steering, WFS). These two methods can be applied simultaneously and have been tested at FACET [6] and recently at FERMI-Trieste. The results are very encouraging showing that setting up the procedure with the required weights (ω_D and ω_W), evaluating and adapting the optimal required corrections, stability and reproducibility are all well behaved, and in both machines emittances in line with the best measurements, or even below, have been obtained, rapidly and almost automatically. The result of the correction at FACET is summarized in figure 7, where the vertical emittance after correction is shown against the weight ω_W , for three points. The initial emittance before correction corresponds to $\omega_W = 0$ and was measured using a quad scan at the end of the corrected section, to be 5.4 μm . The emittance after correction was 1.4 μm at the theoretical optimum $\omega_W = 40$. From repeated measurements, the precision was measured to be $\approx \pm 0.4 \mu\text{m}$. Further studies will be presented in this conference.

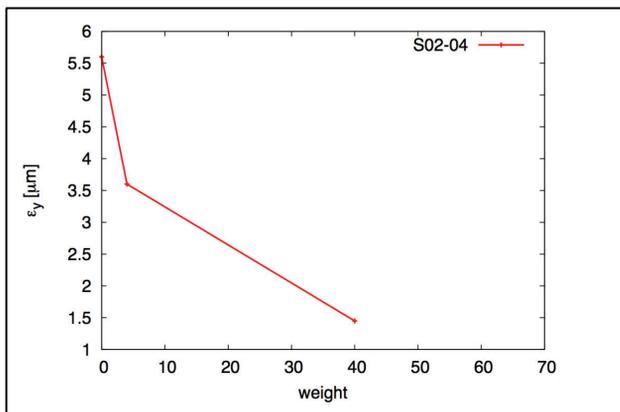


Figure 7: Vertical emittance after WFS as a function of the weight ω_W , measured at the SLAC linac at the end of sector 4 [6].

Free Electron Lasers and Linear Colliders

Fourth generation light sources are based on FELs driven by linacs, with strong links to LC studies.

Of particular relevance to the ILC effort is the construction of the European X-FEL at DESY. With more than 100 cryomodules with design and parameters similar to the nominal ILC cryomodules, the industrial production, assembly and performance of these modules are excellent benchmarks for a future ILC. The statistics for delivered cavities and final modules are increasing rapidly and figure 8 shows the measured gradient of close to 300 cavities [7]. The SLAC LCLS-II project recently approved is expected to provide similar valuable production experiences in the US for this technology.

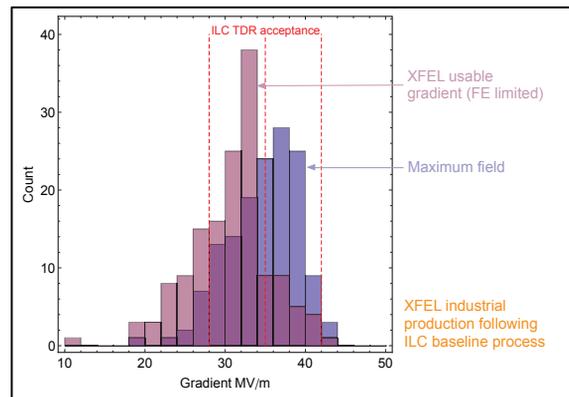


Figure 8: The measured cavity quality for XFEL in average above specifications [7].

On the normal conduction side there are already many FEL facilities constructed or in the construction phase, examples being SLAC (LCLS), Spring-8 (SACLA), Elettra-Sincrotrone Trieste (FERMI), PSI (SwissFEL), etc. The above-mentioned facilities use S-band (3 GHz) or C-band (6 GHz) linacs for generating multi-GeV low emittance beams. Within the CLIC study a number of groups are considering X-band based FELs for extending existing or constructing new complete FELs, due to the potential for compactness, increased flexibilities for repetition rate increases and cost reductions [8] (Fig. 9). Even at modest X-band gradients, a 1 GeV X-band linac element can be housed in less than 20 m, a very attractive solution within a limited available space.

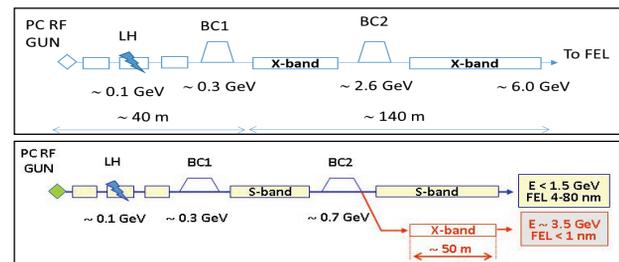


Figure 9: A generic X-band based compact FEL linac layout and a possible FERMI-Trieste upgrade layout with X-band technology [8].

TOWARDS IMPLEMENTATION

On 30 September 2013, the Science Council of Japan (SCJ) submitted a report on the study of the ILC project plans to the Ministry for Education, Culture, Sports, Science and Technology (MEXT) in Japan [9]. SCJ pointed out several common issues with international projects, such as cost sharing, governance model, and availability of scientific and technical leadership and personnel. Therefore, the report recommends the government to allocate the funds necessary to study risks and discuss with potential partners in the next two to three years. The current ILC implementation plans include conclusion of this process, in parallel with international negotiations, leading to potential project construction start around 2018, followed by a ~9 year construction period.

One urgent element of the on-going studies for ILC, beyond technical studies and developments, detector and physics studies and resource planning and international discussions, are detailed site specific civil engineering studies for the ILC underground and surface facilities, adapting the TDR design to a local implementation plan. The site currently recommended is in the Iwate prefecture as shown in figure 10 below, where the geological and seismic conditions are well suited, and where there is very strong regional support for the project.

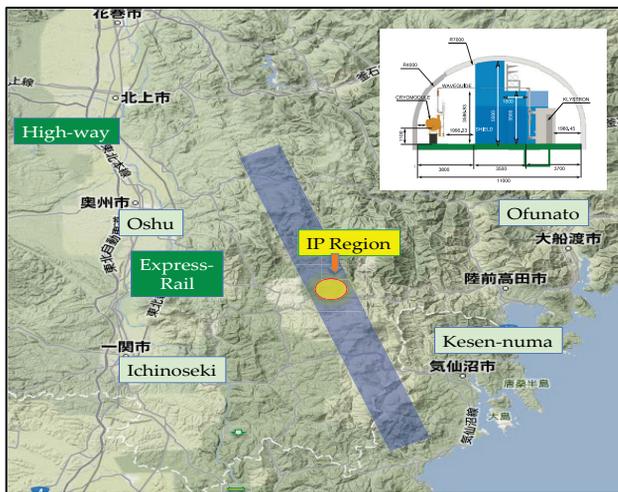


Figure 10: The preferred ILC site ~350km north of Tokyo, and the cross-section of the tunnel divided into a main accelerator part and a shielded klystron gallery/service part.

For CLIC the focus is towards being a possible option for a post LHC machine at CERN addressing energy frontier physics. A large proton-proton ring is another alternative for similar physics goals, and guidance is needed from LHC running at its nominal energy before decisions can be made. The CLIC planning is therefore focussed on technical and industrial developments towards a decision point around 2018-19. Beyond this point larger industry pre-production effort, system developments and detailed site preparation will be needed, before a possible machine construction start-up.

The CLIC project time-line is such that the initial stage of the machine can be ready as the LHC programme reaches its conclusion.

CONCLUSIONS

Future LC can provide exiting physics opportunities both short term for detailed Higgs and top physics measurements, with ILC as the natural tool, and longer term for direct energy frontier physics exploring possible extensions to the Standard Model, with CLIC as the most versatile tool. Both machines studies have developed technologies and methods, in many cases through common or connected activities addressing the key technical and/or performance challenges. Detailed cost and power estimates are also made and documented in [2] and [3]. In particular for CLIC more work is needed to optimised these parameters while ILC have already undergone a significant optimisation in the period 2008-2013 for the TDR. There is a very important technology link between 3rd generation light sources and LC damping rings, and between 4th generation FELs with linacs based on SC or normal conducting RF. The construction of such machines provides an invaluable boost to the LC technology development, experience and industrial base.

ACKNOWLEDGMENT

This brief summary is based on work, presentation and papers from the worldwide LC community and only a small fraction of the on-going work can be mentioned.

REFERENCES

- [1] The LC collaboration: <https://www.linearcollider.org>
- [2] The ILC Technical Design Report Vol. 1 and 3, “Exec. Summary and Acc. Baseline Design”, <http://www.linearcollider.org/ILC/Publications/Technical-Design-Report>
- [3] CLIC CDR Vol. 3, “CLIC study summary”, <http://arxiv.org/pdf/1209.2543v1>
- [4] Y.Yamamoto et al, “Achieving high gradient performance of 9-cell cavities at KEK for the international linear collider”, DOI: 10.1016/j.nima.2013.08.050
- [5] K.Kubo, “Towards ILC: Experiments at ATF”, WEZA01, IPAC’14, Dresden, Germany (2014)
- [6] A.Latina et al., “Tests of Beam-Based Alignment at FACET”, TUPRO065, IPAC’14, Dresden, Germany
- [7] N. Walker, “Energy Frontier Colliders – the road ahead”, ICHEP 2014, Valencia, Spain: <https://indico.ific.uv.es/indico/getFile.py/access?contribId=115&sessionId=17&resId=0&materialId=slide&confId=2025>
- [8] G.D’Auria et al., “X-band technology for FEL sources”, MOPP023, these proceedings, LINAC14, Geneva, Switzerland, 2014
- [9] SCJ report to MEXT, LC news October 2013: <http://newslite.linearcollider.org/2013/10/10/ilc-moves-forward-in-japan>