

The CTF3 test facility at CERN, which has demonstrated CLIC's novel two-beam acceleration technology.

Image credit: Maximilien Brice.



CLIC steps up to the TeV challenge

An updated baseline-staging scenario for CERN's Compact Linear Collider (CLIC) focuses on an optimised initial-energy stage at 380 GeV that will be significantly cheaper than the original design, say **Philipp Roloff** and **Daniel Schulte**.

One of CERN's main options for a flagship accelerator in the post-LHC era is an electron–positron collider at the high-energy frontier. The Compact Linear Collider (CLIC) is a multi-TeV high-luminosity linear collider that has been under development since 1985 and currently involves 75 institutes around the world. Being linear, such a machine does not suffer energy losses from synchrotron radiation, which increases strongly with the beam energy in circular machines. Another option for CERN is a very high-energy circular proton–proton collider, which is currently being considered as the core of the Future Circular Collider (FCC) programme. So far, CLIC R&D has principally focused on collider technology that's able to reach collision energies in the multi-TeV range. Based on this technology, a conceptual design report (CDR) including a feasibility study for a 3 TeV collider was completed in 2012.

With the discovery of the Higgs boson in July of that year, and the fact that the particle turned out to be relatively light with a mass of 125 GeV, it became evident that there is a compelling physics case for operating CLIC at a lower centre-of-mass energy. The optimal collision energy is 380 GeV because it simultaneously allows physicists to study two Higgs-production processes in addition to top-quark pair production. Therefore, to fully exploit CLIC's scientific potential, the collider is foreseen to be constructed in several stages corresponding to different centre-of-mass energies: the first at 380 GeV would be followed by stages at 1.5 and 3 TeV, allowing powerful searches for phenomena beyond the Standard Model (SM).

While a fully optimised collider at 3 TeV was described in the CDR in 2012, the lower-energy stages were not presented at the same level of detail. In August this year, however, the CLIC and CLICdp (CLIC detector and physics study) collaborations published an updated baseline-staging scenario that places emphasis on an optimised first-energy stage compatible with an extension

to high energies. The performance, cost and power consumption of the CLIC accelerator as a function of the centre-of-mass energy were addressed, building on experience from technology R&D and system tests. The resulting first-energy stage is based on already demonstrated performances of CLIC's novel acceleration technology and will be significantly cheaper than the initial CDR design.

CLIC physics

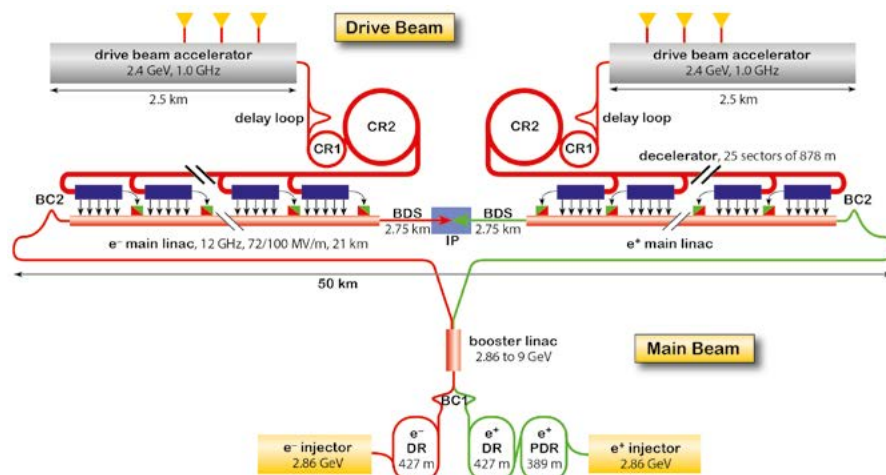
An electron–positron collider provides unique opportunities to make precision measurements of the two heaviest particles in the SM: the Higgs boson (125 GeV) and the top quark (173 GeV). Deviations in the way the Higgs couples to the fermions, the electroweak bosons and itself are predicted in many extensions of the SM, such as supersymmetry or composite Higgs models. Different scenarios lead to specific patterns of deviations, which means that precision measurements of the Higgs couplings can potentially discriminate between different new-physics scenarios. The same is true of the couplings of the top quark to the Z boson and photon. CLIC would offer such measurements as the first step of its physics programme, and full simulations of realistic CLIC detector concepts have been used to evaluate the expected precision and to guide the choice of collision energy.

The principal Higgs production channel, Higgsstrahlung ($e^+e^- \rightarrow ZH$), requires the centre-of-mass energy to be equal to the sum of the Higgs- and Z-boson masses plus a few tens of GeV. For an electron–positron collider such as CLIC, Higgsstrahlung has a maximum cross-section at a centre-of-mass energy of around 240 GeV and decreases as a function of energy. Because the colliding electrons and positrons are elementary particles with a precisely known energy, Higgsstrahlung events can be identified by detecting the Z boson alone as it recoils against the Higgs boson. This can be done without looking at the decay of the Higgs boson,

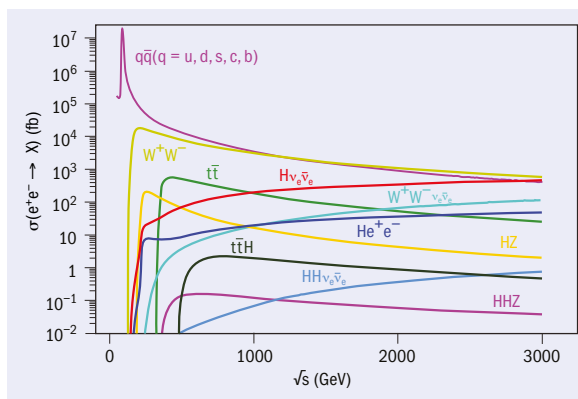
and hence the measurement is completely independent of possible unknown Higgs decays. This is a unique capability of a lepton collider and the reason why the first energy stage of CLIC is so important. The most powerful method with which to measure the Higgsstrahlung cross-section in this way is based on events where a Z boson decays into hadrons, ▷

Combining all available knowledge led to the choice of 380 GeV for the first energy stage.

Compact Linear Collider



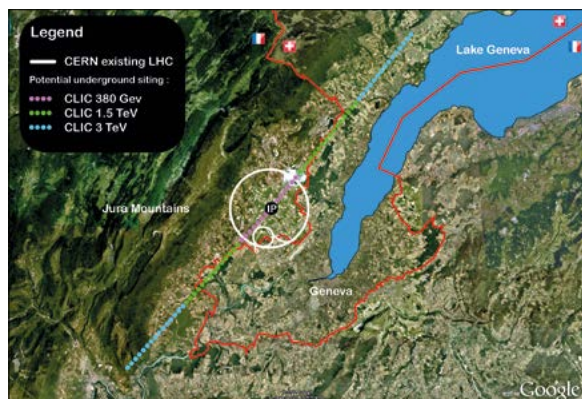
(Left) Overview of the CLIC layout at 3 TeV, showing combiner rings (CR), delay loop, damping ring (DR), pre-damping ring (PDR), bunch compressor (BC) and beam delivery system (BDS). The red and green squares represent beam dumps. (Below) CLIC footprints in the vicinity of CERN, showing the three implementation stages. (Below left) The centre-of-mass energy dependencies of important SM processes in electron–positron collisions.



and the best precision is expected at centre-of-mass energies around 350 GeV. (At lower energies it is more difficult to separate signal and background events, while at higher energies the measurement is limited by the smaller signal cross-section and worse recoil mass resolution.)

The other main Higgs-production channel is WW fusion ($e^+e^- \rightarrow H\nu_e\bar{\nu}_e$). In contrast to Higgsstrahlung, the cross-section for this process rises quickly with centre-of-mass energy. By measuring the rates for the same Higgs decay, such as $H \rightarrow b\bar{b}$, in both Higgsstrahlung and WW-fusion events, researchers can significantly improve their knowledge of the Higgs decay width – which is a challenging measurement at hadron colliders such as the LHC. A centre-of-mass energy of 380 GeV at the first CLIC energy stage is ideal for achieving a sizable contribution of WW-fusion events.

So far, the energy of electron–positron colliders has not been high enough to allow direct measurements of the top quark. At the first CLIC energy stage, however, properties of the top quark can be obtained via pair-production events ($e^+e^- \rightarrow t\bar{t}$). A small fraction of the collider’s running time would be used to scan the top pair-production cross-section in the threshold region around 350 GeV. This would allow us to extract the top-quark mass in a theoretically well-defined scheme, which is not possible at hadron colliders. The value of the top-quark mass has an important impact on the stabil-



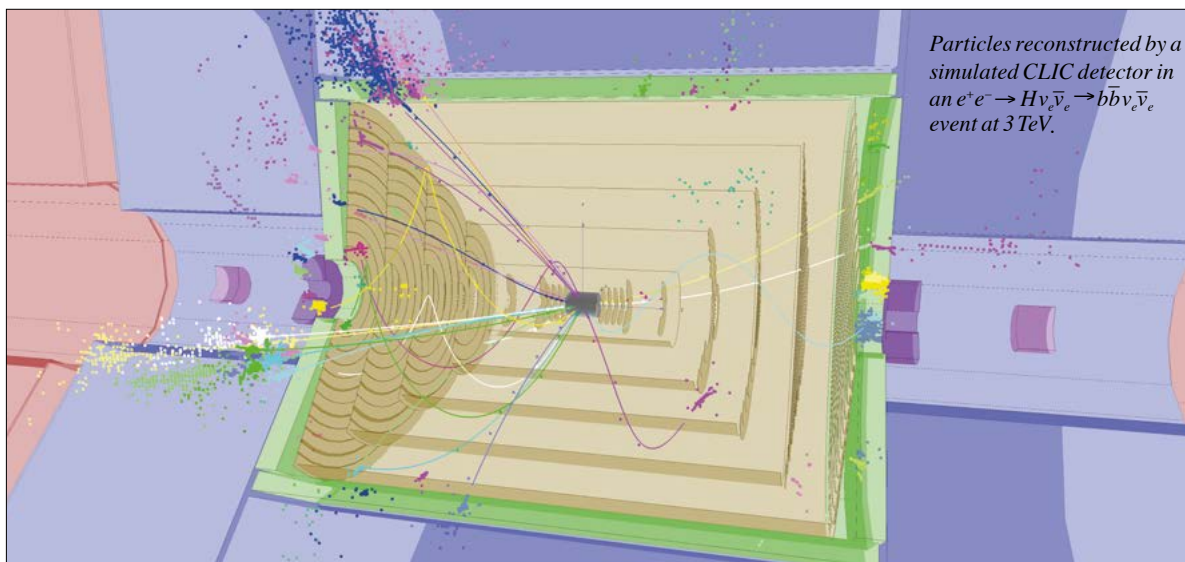
ity of the electroweak vacuum at very high energies.

With current knowledge, the achievable precision on the top-quark mass is expected to be in the order of 50 MeV, including systematic and theoretical uncertainties. This is about an order of magnitude better than the precision expected at the High-Luminosity LHC (HL-LHC).

The couplings of the top quark to the Z boson and photon can be probed using the top-production cross-sections and “forward-backward” asymmetries for different electron-beam polarisation configurations available at CLIC. These observables lead to expected precisions on the couplings which are substantially better than those achievable at the HL-LHC. Deviations of these couplings from their SM expectations are predicted in many new physics scenarios, such as composite-Higgs scenarios or extra-dimension models. It was recently shown, using detailed detector simulations, that although higher energies are preferred, this measurement is already feasible at an energy of 380 GeV, provided the theoretical uncertainties improve in the coming years. The expected precisions depend on our ability to reconstruct $t\bar{t}$ events correctly, which is more challenging at 380 GeV compared to higher energies because both top quarks decay almost isotropically.

Combining all available knowledge therefore led to the choice of 380 GeV for the first-energy stage of the CLIC programme in

Compact Linear Collider



the new staging baseline. Not only is this close to the optimal value for Higgs physics around 350 GeV but it would also enable substantial measurements of the top quark. An integrated luminosity of 500 fb^{-1} is required for the Higgs and top-physics programmes, which could take roughly five years. The top cross-section threshold scan, meanwhile, would be feasible with 100 fb^{-1} collected at several energy points near the production threshold.

Stepping up

After the initial phase of CLIC operation at 380 GeV, the aim is to operate CLIC above 1 TeV at the earliest possible time. In the current baseline, two stages at 1.5 TeV and 3 TeV are planned, although the exact energies of these stages can be revised as new input from the LHC and HL-LHC becomes available. Searches for beyond-the-SM phenomena are the main goal of high-energy CLIC operation. Furthermore, additional unique measurements of Higgs and top properties are possible, including studies of double Higgs production to extract the Higgs self-coupling. This is crucial to probe the Higgs potential experimentally and its measurement is extremely challenging in hadron collisions, even at the HL-LHC. In addition, the full data sample with three million Higgs events would lead to very tight constraints on the Higgs couplings to vector bosons and fermions. In contrast to hadron colliders, all events can be used for physics and there are no QCD backgrounds.

Two fundamentally different approaches are possible to search for phenomena beyond the SM. The first is to search directly for the production of new particles, which in electron–positron collisions can take place almost up to the kinematic limit. Due to the clean experimental conditions and low backgrounds compared to hadron colliders, CLIC is particularly well suited for measuring new and existing weakly interacting states. Because the beam energies are tunable, it is also possible to study the production thresholds of new particles in detail. Searches for dark-matter candidates, meanwhile, can be performed using single-photon events with missing energy. Because lepton colliders probe the coupling of dark-matter

particles to leptons, searches at CLIC are complementary to those at hadron colliders, which are sensitive to the couplings to quarks and gluons.

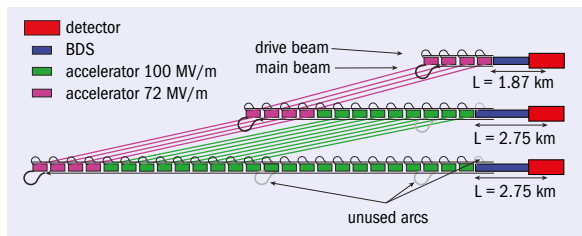
The second analysis approach at CLIC, which is sensitive to even higher mass scales, is to search for unexpected signals in precision measurements of SM observables. For example, measurements of two-fermion processes provide discovery potential for Z' bosons with masses up to tens of TeV. Another important example is the search for additional resonances or anomalous couplings in vector-boson scattering. For both indirect and direct searches, the discovery reach improves significantly with increasing centre-of-mass energy. If new phenomena are found, beam polarisation might help to constrain the underlying theory through observables such as polarisation asymmetries.

The CLIC concept

CLIC will collide beams of electrons and positrons at a single interaction point, with the main beams generated in a central facility that would fit on the CERN site. To increase the brilliance of the beams, the particles are “cooled” (slowed down and reaccelerated continuously) in damping rings before they are sent to the two high-gradient main linacs, which face each other. Here, the beams are accelerated to the full collision energy in a single pass and a magnetic telescope consisting of quadrupoles and different multipoles is used to focus the beams to nanometre sizes in the collision point inside of the detector. Two additional complexes produce high-current (100 A) electron beams to drive the main linacs – this novel two-beam acceleration technique is unique to CLIC.

The CLIC accelerator R&D is focused on several core challenges. First, strong accelerating fields are required in the main linac to limit its length and cost. Outstanding beam quality is also essential to achieve a high rate of physics events in the detectors. In addition, the power consumption of the CLIC accelerator complex has to be limited to about 500 MW for the highest-energy stage; hence a high efficiency to generate RF power and transfer ▷

Compact Linear Collider



The different energy stages of the CLIC design. In the first stage, a different accelerating structure design is used, which can be moved to the beginning of the linacs and reused for the following stages.

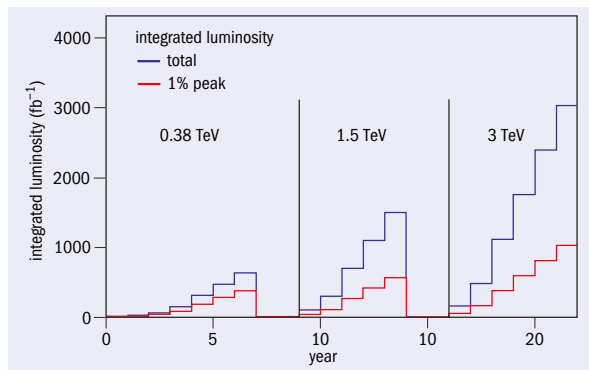
it into the beams is mandatory. CLIC will use high-frequency (X-band) normal-conducting accelerating structures (copper) to achieve accelerating gradients at the level of 100 MV/m. A centre-of-mass energy of 3 TeV can be reached with a collider of about 50 km length, while 380 GeV for CLIC's first stage would require a site length of 11 km, which is slightly larger than the diameter of the LHC. The accelerator is operated using 50 RF pulses of 244 ns length per second. During each pulse, a train of 312 bunches is accelerated, which are separated by just 0.5 ns. To generate the accelerating field, each CLIC main-linac accelerating structure needs to be fed with an RF power of 60 MW. With a total of 140,000 structures in the 3 TeV collider, this adds up to more than 8 TW.

Because it is not possible to generate this peak power at reasonable cost with conventional klystrons (even for the short pulse length of 244 ns), a novel power-production scheme has been developed for CLIC. The idea is to operate a drive beam with a current of 100 A that runs parallel to the main beam via power extraction and transfer structures. In these structures, the beam induces electric fields, thereby losing energy and generating RF power, that is transferred to the main-linac accelerating structures. The drive beam is produced as a long (146 μ s) high-current (4 A) train of bunches and is accelerated to an energy of about 2.4 GeV and then sent into a delay loop and combiner-ring complex where sets of 24 consecutive sub-pulses are used to form 25 trains of 244 ns length with a current of about 100 A. Each of these bunch-trains is then used to power one of the 25 drive-beam sectors, which means that the initial 146 μ s-long pulse is effectively compressed in time by a factor of 600, and therefore its power is increased by the same factor.

To demonstrate this novel scheme, a test facility (CTF3) was constructed at CERN since 2001 that reused the LEP pre-injector

building and components as well as adding many more. The facility now consists of a drive-beam accelerator, the delay loop and one combiner ring. CTF3 can produce a drive-beam pulse of about 30 A and accelerate the main beam with a gradient of up to 145 MV/m. A large range of components, feedback systems and operational procedures needed to be developed to make

The overall three-stage CLIC physics programme would last for 22 years.



Integrated luminosity in the considered staging scenario (years are counted from the start of beam commissioning).

the facility a success, and by the end of 2016 it will have finished its mission. Further beam tests at SLAC, KEK and various light sources remain important. The CALIFES electron beam facility at CERN, which is currently being evaluated for operation from 2017, can provide a testing ground for high-gradient structures and main-beam studies. More prototypes for CLIC's main-beam and drive-beam components are being developed and characterised in dedicated test facilities at CERN and collaborating institutes. The resulting progress in X-band acceleration technology also generated important interest in the Free Electron Laser (FEL) community, where it may allow for more compact facilities.

To achieve the required luminosities ($6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at 3 TeV), nanometre beam sizes are required at CLIC's interaction point. This is several hundred times smaller than at the SLC, which operated at SLAC in the 1990s and was the first and only operational linear collider, and therefore requires novel hardware and sophisticated beam-based alignment algorithms. A precision pre-alignment system has been developed and tested that can achieve an alignment accuracy in the range of 10 μ m, while beam-based tuning algorithms have been successfully tested at SLAC and other facilities. These algorithms use beams of different energies to diagnose and correct the offset of the beam-position monitors, reducing the effective misalignments to a fraction of a micron. Because the motion of the ground due to natural and technical sources can cause the beam-guiding quadrupole magnets to move, knocking the beams out of focus, the magnets will be stabilised with an active feedback system that has been developed by a collaboration of several institutes, and which has already been demonstrated experimentally.

CLIC's physics potential has been illustrated through the simulation and reconstruction of benchmark physics processes in two dedicated detector concepts. These are based on the SiD and ILD detector concepts developed for the International Linear Collider (ILC), an alternative machine currently under consideration for construction in Japan, and have been adapted to the experimental environment at the higher-energy CLIC. Because the high centre-of-mass energies and CLIC's accelerator technology lead to relatively high beam-induced background levels for a lepton collider, the CLIC detector design and the event-reconstruction techniques are both optimised to suppress the influence of these

Compact Linear Collider

backgrounds. A main driver for the ILC and CLIC detector concepts is the required jet-energy resolution. To achieve the required precision, the CLIC detector concepts are based on fine-grained electromagnetic and hadronic calorimeters optimised for particle-flow analysis techniques. A new study is almost complete, which defines a single optimised CLIC detector for use in future CLIC physics benchmark studies. The work by CLICdp was crucial for the new staging baseline (especially for the choice of 380 GeV) because the physics potential as a function of energy can only be estimated with the required accuracy using detailed simulations of realistic detector concepts.

The new staged design

To optimise the CLIC accelerator, a systematic design approach has been developed and used to explore a large range of configurations for the RF structures of the main linac. For each structure design, the luminosity performance, power consumption and total cost of the CLIC complex are calculated. For the first stage, different accelerating structures operated at a somewhat lower accelerating gradient of 72 MV/m will be used to reach the luminosity goal at a cost and power consumption similar to earlier projects at CERN – while also not inflating the cost of the higher-energy stages. The design should also be flexible enough to take advantage of projected improvements in RF technology during the construction and operation of the first stage.

When upgrading to higher energies, the structures optimised for 380 GeV will be moved to the beginning of the new linear accelerator and the remaining space filled with structures optimised for 3 TeV operation. The RF pulse length of 244 ns is kept the same at all stages to avoid major modifications to the drive-beam generation scheme. Data taking at the three energy stages is expected to last for a period of seven, five and six years, respectively. The stages are interrupted by two upgrade periods each lasting two years, which means that the overall three-stage CLIC programme will last for 22 years from the start of operation. The duration of each stage is derived from integrated luminosity targets of 500 fb⁻¹ at 380 GeV, 1.5 ab⁻¹ at 1.5 TeV and 3 ab⁻¹ at 3 TeV.

An intense R&D programme is yielding other important improvements. For instance, the CLIC study recently proposed a novel design for klystrons that can increase the efficiency significantly. To reduce the power consumption further, permanent magnets are also being developed that are tunable enough to be able to replace the normal conducting magnets. The goal is to develop a detailed design of both the accelerator and detector in time for the update of the European Strategy for Particle Physics towards the end of the decade.

Mature option

With the discovery of the Higgs boson, a great physics case exists for CLIC at a centre-of-mass energy of 380 GeV. Hence particular emphasis is being placed on the first stage of the accelerator, for which the focus is on reducing costs and power consumption. The new accelerating structure design will be improved and more statistics on the structure performance will be obtained. The detector design will continue to be optimised, driven by the requirements of the physics programme. Technology demonstrators for the most challenging detector elements, including the vertex detector and main tracker, are being developed in parallel.

Common studies with the ILC, which is currently being considered for implementation in Japan, are also important, both for accelerator and detector elements, in particular for the initial stage of CLIC. Both the accelerator and detector parameters and designs, in particular for the second- and third-energy stages, will evolve according to new LHC results and studies as they emerge.

CLIC is the only mature option for a future multi-TeV high-luminosity linear electron–positron collider. The two-beam technology has been demonstrated in large-scale tests and no show stoppers were identified. CLIC is therefore an attractive option for CERN after the LHC. Once the European particle-physics community decides to move forward, a technical design will be developed and construction could begin in 2025.

Further reading

H Abramowicz *et al.* 2016 arXiv:1608.07538.

CLIC and CLICdp Collaborations 2016 arXiv:1608.07537.

Résumé

Le CLIC s'attaque au défi des TeV

Le collisionneur linéaire compact (CLIC) est un collisionneur linéaire à haute luminosité de plusieurs TeV, en développement depuis 1985, pour lequel un rapport préliminaire de conception a été achevé en 2012. Avec la découverte du boson de Higgs en juillet de la même année, l'intérêt indiscutable d'une exploitation du CLIC à une énergie dans le centre de masse plus faible (380 GeV) est devenu évident. Récemment, CLIC a publié une mise à jour de son scénario de base, étape par étape; il met l'accent sur une première étape d'énergie optimisée. Cette première étape est basée sur des performances déjà démontrées de la technologie d'accélération novatrice du CLIC, et elle sera nettement moins onéreuse que celle figurant dans le rapport préliminaire de conception initial.

Philipp Roloff and Daniel Schulte, CERN.

Italy at CERN 2017



The CERN ILO for Italy has the great pleasure to announce that the next edition of **Italy at CERN 2017** is going to take place in **Geneva on April 4 – 7, 2017**.

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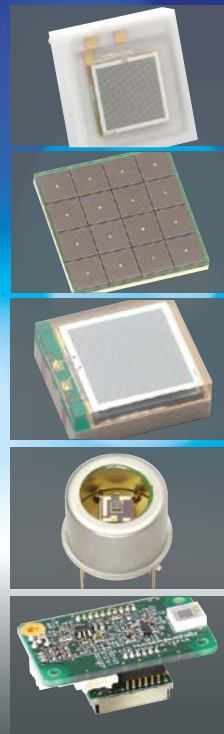
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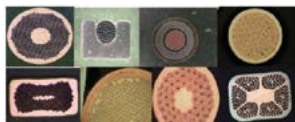
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Factory Acceptance Testing at Buckley Systems



Mobile "Roamer" CMM used to confirm dimensions are within tolerance on a quadrupole magnet.

General

Buckley Systems manufactures sophisticated magnets, and it is certified ISO 9001:2008 for the following scope: the design and manufacture of precision electromagnets, ion-beam physics hardware, and ultra-high vacuum equipment used in the semiconductor - ion implant industry, laboratory research and particle accelerators. Nevertheless, from the customer's point of view, the manufacturing job is not complete until the Factory Acceptance Test (FAT) is successfully completed. Buckley System "FATs" are described in the Coils, and Magnets sections.

A Quality Control (QC) programme is in place to ensure that machined parts and assemblies meet dimensional tolerances (and other specified customer constraints) throughout the manufacturing process. Several high-accuracy Coordinate Measuring Machines (CMM) measure dimensions to 10 μm including a "roamer" which has "touchscan" capability meaning that its finger can be drawn along a surface rather than just touching a surface at several points. Ceramic gauge blocks measure magnet gaps to 1 μm accuracy.

Coils

Buckley Systems achieves FATs for National Laboratories that are comprehensive and stringent. All measurements within the temperature controlled test building must be within a set tolerance to achieve a pass. A sample list of typical measurements follows:

- (i) electrical resistance tests,
- (ii) inductance tests,
- (iii) pressure and flow rate tests of the cooling water,
- (iv) insulation resistance and high electric potential tests with coils immersed in salted water ($< 1,000 \Omega\cdot\text{m}$) and leakage currents $< 50 \mu\text{A}$,
- (v) impulse-tested for turn-to-turn integrity over a range of voltages with rejection based on frequency shifts or damping rates changing as a function of voltage, or non-conformance to customer supplied waveforms
- (vi) thermal-switch open/close testing as a function of temperature.
- (e) magnetic length, and (f) field angle,
- (iv) Leak rate tests for high vacuum and ultra high vacuum chambers with the appropriate bake-out procedures observed.

Lastly, Buckley Systems can model particle trajectories through the measured magnetic fields and compare the magnet's performance based on the measured fields to the simulated performance. This has been particularly useful in ascertaining whether magnetic spectrometer systems have achieved their design resolution or not.

Magnets

Buckley Systems accommodates magnets with apertures ranging from 8 mm to 2000 mm, and has Hall probes with 3.5 m of travel at its disposal. Completed magnets must also undergo FATs and a sampling of what these entail follows:

- (i) the nominal mechanical resonant frequency orthogonal to the magnet axis,
- (ii) Magnetic measurements for dipole magnets through a range of excitation-currents include for example:
 - (a) integrated field homogeneity to one part in 10^4 over a "good field" range in the mid-plane, (b) integrated dipole field over length of yoke and including fringe field region, (c) end field maps and chamfer adjustments to minimize integrated field errors, and (d) B/I curve at the midpoint,
- (iii) Magnetic measurements for quadrupole, sextupole, and octupole magnets over a range of excitation-currents include:
 - (a) integrated field harmonics up to a maximum-pole (42-pole in some cases) at a set radius, (b) integrated field measurements over length of yoke and including fringe field region, (c) end chamfer adjustments to minimize integrated harmonic terms of the customer's choice, (d) magnetic centre measurement to better than ± 50 microns,



Magnetic Field Measurements on a Dipole Magnet.



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